Development of Structural Lightweight Concrete Utilizing Local Materials

BY

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Dedication

To my beloved parents, brothers, sisters, and whole family for their endless love and support

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All praise is due to Allah for giving me knowledge, effort and patience to finish with this work. May His peace and blessings be upon the best of mankind, Muhammad Ibn Abdillaah (SallaLLaahualayhiwasallam), his household, his companions and those who follow his right path of guidance till the day, I would like to take the opportunity to thank King Fahd University of Petroleum and Minerals (KFUPM), representative by the Department of Civil and Environmental Engineering, Dhahran, Saudi Arabia, for providing me an opportunity to successfully complete my M.Sc. in Structure Engineering. My special appreciation and thanks extend to my thesis committee, advisor Dr. Salah U. Al-Dulaijan, and committee members Dr. Mohammad Maslehuddin and Dr. Shamshad Ahmad for their brilliant suggestion, comment, continue guidance, support, and cooperation during my work on this thesis, the words is not enough to evaluate their great efforts that made this task possible, by Allah's will. I am also thankful to the Chairman of the Department of Civil and Environmental Engineering, all staff, faculty members, research institute engineers, Eng. Mohammed Rizwan Ali and Eng. Mohammed Salihu Barry, concrete and structure laboratory engineers and technician, for providing the knowledge, time, and facilities to complete my study. A lot of thanks express to my classmates in KFUPM for the nice friendships. Much thanks to my roommate Mr. Mohammed Abdul Salam Hanfi, M.Sc. student in Petroleum engineering, for his sincere brotherhood and nice moments we had been together throughout our study in KFUPM. Much of thanks to my friends, colleagues and all the good people, far and near, who have encouraged me during my work in this research.

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THESIS ABSTRACT (ENGLISH)

Full Name: **Ahmed, Mahmoud Nasr Mahmoud**

Thesis Title: **Development of Structural Lightweight Concrete Utilizing Local Materials**

Major Field: **Civil Engineering (Structures)**

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The use for structural lightweight concrete in structural elements is gaining importance due to its benefit in reducing dead load, as well as advantages related to thermal and noise insulation, cost effectiveness, reduction in member size, enhanced fire resistance and environmental protection by reducing CO_2 emission. In general, structural lightweight concrete is used in structures to reduce the self weight and to decrease the earthquake damage risks.

The aim of this study was to develop structural lightweight concrete (SLWC) with the use of local available natural light weight aggregates, such as expanded perlite and scoria aggregate, artificial aggregates, like polypropylene, and industrial waste byproduct like oil ash, with low thermal conductivity. The advantages of the developed production will be a reduction in the overall weight of the structure and energy conservation due to the low thermal conductivity.

The developed SLWC produced with these materials had acceptable compressive and flexural strength concrete with the same range as traditional concrete and low unit weight. Most of the SLWC samples had low chloride permeability (RCPT), high to moderate corrosion resistance, drying shrinkage within the acceptable limit, and very low thermal conductivity. Based on the findings of the study, it was recommended to use Perlite-Scoria combination group as SLWC concrete in Saudi Arabia satisfying the mechanical, thermal, and durability requirements.

DEGREE OF MASTER OF SCIENCE
KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
DHAHRAN, SAUDI ARABIA

THESIS ABSTRACT (ARABIC)

الإســـم الكامل: **محمود نصر محمود أحمد**

عنوان الرسالة: **تطوير خرسانه انشائيه خفيفه باستخدام المواد المحليه**

التـــخصـــص: **الهندسه المدنيه (انشاءات)**

تاريـخ الـدرجـة العلمية: **ديسمبر،2014 م**

استخدام الخرسانه الانشائيه الخفيفه في الاعضاء الانشائيه يحصل على أهميه بسبب فوائده في تقليل الحمل الميت بالاضافه الى فوائد تتعلق بالعزل الحراري والصوتي, فعالية تكلفة البناء, تقليل مقاس الاعضاء, تعزيز مقاومة الحرائق وحمايه البيئه بتقليل انبعاث غاز ثاني أكسيد الكربون. من ناحيه عامه, تستخدم الخرسانه الانشائيه الخفيفه في المنشأت لتقليل الوزن الذاتي و مخاطر الاصابات الزلزاليه.

الغرض من هذه الدراسه هو تطوير خرسانه انشائيه خفيفه باستخدام انواع من الركام الطبيعي الخفيف المتوفره محليا, مثل ركام البرلايت و سكوريا, الركام الصناعي, مثل البوليبروبيلين, ومخلفات الصناعه الثانويه مثل الاويل آش, بتوصيل حراري ضعيف.فوائد المنتج المطور ستكون في تقليل الوزن الكلي للمنشأه وتوفير الطاقه الناتج من التوصيل الحراري الضعيف.

الخرسانه الانشائيه الخفيفه المطوره لها مقاومات انضغاط وثني مقبوله في حدود مقاومات الخرسانه التقليديه. أغلب العينات لها نفاذيه ضعيفه للاملاح, مقاومه بين العاليه والمتوسطه للتآكل, معدلات انكماش في الحدود المقبوله, وتوصيل حراري ضعيف جدا. وبناءا على مستخرجات هذه الدراسه, يوصى باستخدام المجموعه المتكونه من البرلايت والاسكوريا كخرسانه انشائيه خفيفه في المملكه العربيه السعوديه لتحقيقها المتطلبات الميكانيكيه, الحراريه, ومتطلبات الديمومه.

درجة الماجستير في العلوم

جامعة الملك فهد للبترول والمعادن

الظهران، المملكة العربية السعودية

CHAPTER 1

INTRODUCTION

1.1 Introduction to Structural Lightweight Concrete

Lightweight concrete (LWC) is a concrete that contains cement and lightweight aggregates. It has a bulk density ranging between 300 and 2,000 kg/m^3 compared to a value of 2,200 to 2,600 kg/m^3 of normal weight concrete(NWC). LWC can be divided into structural lightweight concretes and ultra-lightweight concretes for non-structural purposes. ACI Committee 213 [2] makes three divisions on the basis of strength and unit weight: Low-density, low-strength concrete used for insulation, Moderate-strength lightweight concrete used for concrete block and other applications where some useful strength is desirable and Structural lightweight concrete (SLWC) used for structural elements. According to ACI 213, SLWC is structural concrete made with lightweight aggregate; the unit weight at 28 days is between 1440 kg/m^3 to1850 kg/m^3 and the compressive strength is more than 17.2 MPa. However, ACI 213 definition continues to allow unit weight up to 1900 kg/m^3 [2]. The reduced bulk density of SLWC is due to the addition of a void system within the cementations mass. This can be made by three methods:

i. Using high porosity natural or artificial Light weight aggregates.

ii. Adding small polystyrene balls totally or partially to normal concrete.

iii. Introducing a substance that has ability to develop gases in an alkaline environment.

Usually, SLWC is made by changing all or parts of normal weight aggregates by light weight aggregate using natural or artificial aggregates which are available in different parts of the world [3].

SLWC gives a lot of technical, environmental, and economical advantages and it is in the way to become a prevalent material in the near future. It has been upgraded in properties like the strength, workability, lighter dead load and resistance to freezing and thawing [1, 48-49]. It is also known for its better long-term durability, therefore, the use of SLWC is rapidly increasing [1, 50]. There are clear advantages of SLWC over the NWC. SLWC has greater strength/weight ratio [3, 51], less thermal conductivity coefficient [3, 52, 53], superior fire resistance [3, 54], and better durability properties [3, 55, 56]. The use of SLWC decreases the dead load lead to reduce the sizes of columns, beams, walls, and foundation and therefore reduce the resulting seismic loads and earthquake damage which is proportional to the weight of the structure [3, 57]. But the most significant potential advantage of the use of SLWC is the environmental protection. If the raw materials needed for the production of SLWC are derived from natural sources and industrial waste products, the environment and economy of the country stands to benefit. Also, it will result in a significant reduction in the greenhouse gas emissions by reducing the need of large quantities of cement whose production is a major contributor to CO_2emission. These inherent superior advantages over traditional concrete make SLWC widely accepted.

There has been a rising demand for SLWC in many applications of recent construction for technical, economic, and environmental considerations [7, 31]. Although some research on the properties of SLWC has been conducted in different parts of the world, data are lacking on its development in the Kingdom. Thus, the aim of the study is to investigate SLWC utilizing local materials as much as possible. The produced SLWC should have high thermal resistance and it should be durable and economical.

1.2 Need for this research

Given the SLWC excellent attributes and the trends of adoption in various parts of the world, as discussed in the previous section, it is very important to encourage local construction industry to adopt the idea. Although, a handful of construction projects in the kingdom have employed SLWC recently, it’s still not fully adopted locally.

SLWC has economic benefits because of low heat conductivity and unit weight. Since cement is the most widely used material in the construction industry; it is the main ingredient in concrete. The process of manufacturing of cement is a source of greenhouse gas emission. Today, there is a need to meet the increasing demand for concrete worldwide without a parallel increase in greenhouse gases. Since SLWC has low density, structures made with SLWC will have smaller structural members and lesser foundation depth. This will decrease the overall consumption of cement in a structure which will definitely lead to a reduction in the greenhouse gas emission.

This research is intended to design SLWC by use of local materials and industrial byproducts to develop more economical and environment friendly (cleaner) concrete by achieving mechanical and durability properties of the NWC. Some researches have been conducted using natural and artificial aggregates, in many parts of the world. In Saudi Arabia there is a need to develop SLWC utilizing locally available materials and industrial byproducts. Materials, such as expanded perlite aggregates, Scoria which are largely available in the Kingdom of Saudi Arabia, can be utilized for the production of SLWC. Moreover, industrial byproducts, such as oil fuel ash, can be used. Therefore, the consumption of waste materials that are generated in abundance during the manufacture of building and other materials in the Kingdom of Saudi Arabia is a noble task that will certainly lead to a greener environment. Further, the usage of these waste cheap materials in concrete will produce economical building materials. Hence, there is a growing need to utilize locally available waste materials to develop SLWC.

1.3 Objectives of the Research

The main objective of this study was to develop high performance SLWC using local natural materials and/or industrial byproducts. The specific objectives were the following:

i. Develop SLWC utilizing local natural materials and/or industrial byproducts,

ii. Evaluate the mechanical and thermal properties and durability characteristics of the developed SLWC, and

iii. Recommend avenues of application of the developed SLWC.

1.4 Research Scheme

The work was carried out in six phases. The first phase contains a comprehensive literature review to develop the information on the subject. The second phase concerned the forming of the program of research based on the collected information in the first phase and the objectives of research. In the third phase, the tasks entailed fabrication, preparation and calibration of testing equipments and weighing scales, preparation of test specimens moulds and experimental accessories. The fourth phase contained conducting trial mixtures and the evaluation of their properties. Mixtures meeting the weight and strength requirements were selected for detailed evaluation of their mechanical, thermal, and durability properties. The fifth phase contained preparing SLWC specimens for the proposed hardened tests on the selected mixes. The specimens were cured in water at the laboratory ambient temperature for 28 days, after which they were taken out for testing. Finally, the experimental data were analysed and models obtained for the relationship among various fresh and hardened mechanical and durability properties. In the final phase, the whole process report was prepared in which experimental results, conclusions and recommendations were presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Uses of Structural Lightweight Concrete

The use of SLWC in different applications, including: floors, roofs, plates, bridges, pre-cast and pre-stressed elements, etc. SLWC is used in seismic zones to give better seismic resistance to the buildings. SLWC was used in the past in some Babylonian buildings, in the 3rd millennium B.C, and in Roman and Greek buildings, with natural aggregates like scoria, and pumice. Many ancient building exists till now [4]. Also, SLWC has been used in USA Park Plaza Hotel, Kansas City, built in 1920. Itis considered as the first structure built with LWC. After that, in 1950s, multi-story buildings and many big structures were built using lightweight concrete, such as Bank of America Corporate Center, and the Lake Point Towers. Also, it is used in highways, bridges and offshore drilling platform [5].In bridges, self-weight of the deck and girders contribute to a significant portion of the load [8, 45-47]. If lightweight concrete is used in putting together these decks and girders, it would be definitely beneficial in reducing the weight of the superstructure, leading to reductions in the size of girders, substructure and foundation. This would eventually result in economic benefits, considering the facilitation in handling, shipping and construction or replacement of bridge elements due to reduced sizes and weights.

Although SLWC has been used successfully for structural purposes in many years, in recent application, there is an increase in the demand for SLWC that has lower density that leads to lower gravitational loading of structures that lower earthquake forces. Recently, due to the development of concrete technology, the production of high performance structural lightweight concrete supported the use the SLWC in building technology.

Al-Khaiat et al. [31] reported that structural lightweight concrete has its obvious advantages of higher strength/weight ratio, better tensile strain capacity, lower coefficient of thermal expansion, and superior heat and sound insulation characteristic due to air voids in the lightweight aggregate.

2.2 SLWC Materials

Many studies have been done in the past two decades on many materials to be utilized as lightweight aggregates to produce SLWC. Many natural and artificial aggregates have been utilized to prepare SLWC.

2.2.1 Expanded Perlite Aggregate

Expanded perlite is one of the lightweight aggregates that can be utilized for the production of SLWC. Perlite is a type of glassy volcanic rock originating from lava of strictly determined chemical composition and crystalline water content (2-5%). The perlite rock is crushed, dried and graded. When perlite grains are abruptly subjected to immediate heat near to their softening point (870^{o}C) the combined water rapidly vaporizes causing them to expand 4 to 20 times their original volume [34-36]. The heating process does not change the perlite density (2.2–2.3 kg/dm^3) but the bulk density decreases to 60–80 g/dm^3 [35].The expansion process creates countless air voids in the grains which account for the lightweight and excellent insulating properties of expanded perlite.

Perlite is basically the mineral obsidian. Perlite mineral deposit exist in many countries of the world, but the expanded product is only available in countries which have commercial expanding plants [34,37].In Saudi Arabia there is Saudi perlite industries factory .

Expanded perlite aggregate (EPA) is lightweight material having ability to insulate heat and sound that benefit the constructions economically. EPA used in constructional elements, like bricks, pipe, and wall and floor blocks to reduce the weight of the structure, but it is not used largely in concrete [6,38].

Most of high rise buildings are affected by the earthquake due to the higher density of concrete, so by reducing the unit weight using EPA give the solution to reduce the damage due the earthquakes [6,39-42]. In some studies EPA was used as admixture in cement or used as aggregate in concrete. Also it is used as replacement of fine aggregates in various ratios depending on the target strength. As itisknown, the effect of perlite aggregate increases as the curing period increases [6,25]. In spite of a decrease in the density and strength with the replacement of perlite aggregate in the concrete mix, perlite aggregate is used as alternate to the mineral admixture, such as fly ash and silica fume to get better mechanical properties and reduced permeability[6,43].

I˙lker et al. [6] studied the properties of the lightweight concrete using perlite aggregate in different percentages replacing fine aggregates (sand), different cement types and different cement contents. They reported that compressive and split tensile strength best results were noted from the dosage of 15-30% at cement content of 350-400 kg/m^3 of type CEM 42.5R.

Khonsari et al. [1] investigated the effects of different percentages of expanded perlite aggregates replacing the coarse aggregates on concrete properties, such as: compressive strength in two different curing conditions, tensile strength and sulfate attack. He studied the effect of adding different type of steel fibers to 10% perlite aggregate. He reported that the compressive strength decreased by increasing the percentage of the perlite in the mix. Also, the EPA reduced the heat of hydration and needed more curing duration.

Turkman[24] found that drying shrinkage of concrete is reduced by the use of expanded perlite aggregate and the drying shrinkage of EPA concrete is lower than that of normal concrete in moisture condition and higher in drying condition.

Demirbog˘a [25] studied the effect of silica fume (SF) and fly ash (FA), as a replacement of cement in a ratio of 10%, 20%,30% by weight ,on the thermal conductivity of lightweight aggregate concrete made of expanded perlite (EPA)and pumice aggregate (PA). Both SF and FA had a decreasing effect on thermal conductivity. EPA (used in place of PA) also induced a decrease of 43.5% in thermal conductivity of concrete.

2.2.2 Basaltic Pumice (Scoria)

One of the natural aggregates that are used for developing SLWC is scoria. It is a volcanic rock. It is dark in color (generally dark brown, black or purplish red), and basaltic or andesitic in composition. Scoria has relatively low mass, but in contrast to pumice, scoria has a specific gravity greater than 1, and sinks in water.

Explosions have formed numerous scoria pyroclastic cones within the basaltic lava fields in western Saudi Arabia. These basaltic lava fields are locally known as harrats and they extend in a north-south direction covering about 180,000 km^2 [26],as shown in Figure 2.1.

Figure 2.1: location of scoria aggregate in western Saudi Arabia.

The dry bulk specific gravity, saturated surface dry bulk specific gravity, and apparent specific gravity values of scoria samples retained on sieve #4 (4.75 mm; coarse aggregate) and the material passing it (fine aggregate) were determined according to ASTM C-127 and C-128, respectively [26] as shown in Figure 2.2.

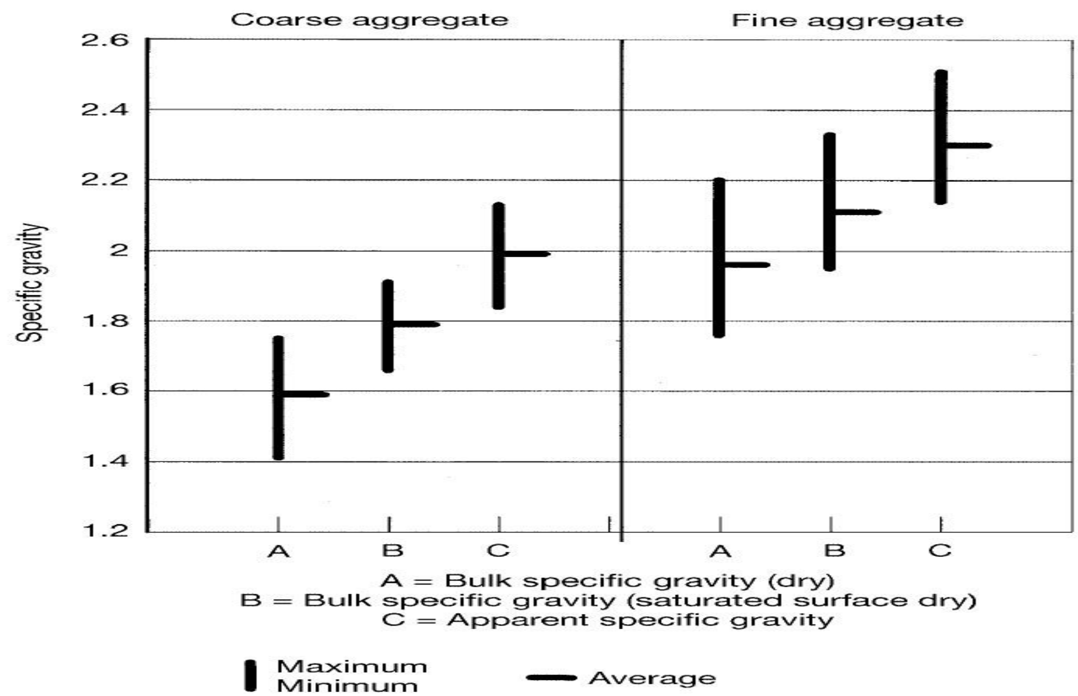


Figure 2.2: Specific gravity of scoria.

Rodded bulk density of scoria samples, tested according to ASTM C-567, is about 866 kg/m^3, and an average loose density of 776 kg/m^3. Maximum dry loose unit weight, according to ASTM C-330, C-331 and C-332, is 880 kg/m^3 for coarse aggregate and 1040 kg/m^3 for combined coarse and fine aggregate [26]. The water absorption of coarse aggregate is between 9.0 and 20%, with an average of 13.1%, and that of fine aggregate between 4.3 and 11.1%, with an average of 7.5% [26]. For lightweight aggregatewater absorption can be up to 30% [26, 44]. It has a Great effect on the workability of the mix design and the concrete mix needs more w/c ratio. The physical properties, such as specific gravity, bulk density, absorption, deleterious material content and petrography were found to be acceptable by ASTM standards.

Many applications can be performed by the use of scoria; it can be used for thermal insulating building blocks, and as a source of Pozzalan in cement production [26].

Shannag et al. [8] investigated the use of volcanic scoria rocks found in north western region of Saudi Arabia (Al-Madina) for developing structural lightweight concrete. They found that volcanic scoria is suitable to be used as fine and coarse aggregate to produce structural lightweight concrete. The developed SLWC had a compressive strength between 18-48 MPa, The splitting tensile and flexural strength of about 9-11% and 10-15% of the compressive strength, respectively.

Moufti et al. [9] used scoria as lightweight fine and coarse aggregates in different percentages. They found that the compressive strength values are acceptable according to the requirement of structural concrete. Pozzolanic activity was tested according to the Italian standards and found to be acceptable. The strength activity index with Portland cement and the effectiveness of scoria admixture in controlling alkali-silica reactions were tested according to ASTM standards. Mortar cubes were prepared for these studies using different mixes and different storage procedures. The results satisfied the ASTM requirements as cement additive. Acceptable results were obtained when scoria was tested for using as heat-insulating material. This fact suggests it could be utilized in the manufacture of building blocks. It was recommended to investigate the other scoria deposits, exploit the economically feasible ones and utilize them for different industrial applications. The study concluded that the manufacture of heat-insulating concrete or building blocks using scoria is of prime importance as an energy saver.

Yasar et al. [10] investigated the use of scoria (basaltic pumice) in developing structural lightweight concrete and the use of scoria and fly ash to develop economical and environment friendly lightweight concrete. The cement content used was 500kg/m^3 and fly ash was 20% replacing the cement. The resulting dry density was 1860kg/m^{3}and 1850 kg/m^3(20% fly ash) and the 28-days compressive strength was 28 MPa and 29 MPa, respectively. It is mentioned that 25MPa compressive cylindrical compressive strength can be made with light weight aggregate. SLWC can be developed economically with the use of fly ash.

Kilic et al. [11] also studied the development of high strength lightweight concrete using scoria aggregates and fly ash and silica fume as mineral admixture replacing the cement. The compressive strength was 30 MPa with scoria, 30 MPa economical light weights concrete with 20% fly ash, and 40Mpa with 10% of silica fume.

2.2.3 Limestone

Limestone, a very common sedimentary rock, mainly consists of mineral calcite of a biochemical origin. 'Dirty limestone' is filled with lots of minerals other than calcite and sand. Limestone can be found in the beds of evaporated seas and lakes and from the shells of sea animals. Limestone is an important building material in humid region, but it is not strong as sandstone because it is easily weathered by acid. It is consider the main source of lime in cement. Limestone density is between 2,500–2,650 kg/m^3, water absorption of less than 1 %, hardness of 3–4 on Moh's scale, and compressive strength of 180–210 MPa [27].

Sajedi et al. [27] used limestone with mineral and chemical admixture to produce high strength structural light weight concrete (HSSLWC) using light weight expanded clay aggregate (LECA) to increase the strength and reduce the porosity. Lightweight structural concrete (LWSC), with a dry density in the range of 1610-1965 kg/m^3 and compressive strength in the range of 34-67MPa was achieved using Leca. It is noticed that using limestone increase the flexural up to 40% in flexural strength results, without a noticeable increase in the specific gravity [27].

2.2.4 Polypropylene

Polypropylene (PP) is a tough, flexible and reasonably economical thermoplastic polymer made from the monomer propylene**.** It is rugged and unusually resistant to many chemical solvents, bases and acids. This allows polypropylene to be used as a plastic. It is often opaque or colored. It has good resistance to fatigue. Hydrocarbon slurry or suspension, bulk slurry and gas phase are the three manufacturing processes to produce polypropylene.

Polypropylene beads were used in the mixture proportioning with coarse pumice aggregate to develop lightweight concrete by Farnam et al. [13].

Bing et al. [14] produced SLWC by replacing fine and coarse aggregates partially or totally by expanded polystyrene beads (EPS).They added polypropylene (PP) fibers and silica fume (SF) to upgrade the shrinkage and mechanical properties. They found that SF improves the bond strength between the cement paste and the EPS beads and therefore improving the compressive strength, Also results show better drying shrinkage properties with PP fibers. They mentioned that the strength reduced by increasing the volume fraction of EPS.

2.2.5 Oil Ash

A local constituent that can be used in the production of SLWC is the industrial byproduct Oil Ash. (OA) a very fine (passes sieve #200) black powder of waste material resulted from heavy fuel burned in a power generation plant. Large quantities of OA are produced and with increase in its quantity open the area of using this byproduct in useful practices to save the environment and eliminate the need for disposal areas.

OA was identified as a non-pozzolanic material has very high specific surface and lower relative density compare to cement [28].The low density of OA and the fine size of particle encourage its use to produce SLWC.

Al-Methel et al. [12] mentioned that OA can be used up to 5% replacing the cement to decrease 50% of the 28-days chloride permeability of concrete compared to ordinary concrete. Also, the addition of OA to concrete in a percentage of 10% increases the 28-days compressive strength by 25% and reduces the chloride permeability by 50% and more, compared to ordinary concrete.

CHAPTER3

EXPERIMENTAL PROGRAM

3.1 Introduction

In this chapter the experimental program and materials, along with their characteristics and sources, used for the study are presented**.** The study aimed to develop SLWC concrete with the use of local available natural light weight aggregates, such as expanded perlite aggregate and scoria aggregate, artificial aggregates, like polypropylene, and industrial waste byproduct like OA in addition to normal weight aggregates.

The research work was executed in three major stages. The first stage involved selection and acquisition of the light weight aggregates, waste materials, and chemical admixtures and designing the trial mixtures for selected combinations of the materials. In the second stage, the optimal characteristics required for obtaining SLWC were obtained. This was done by running several trials and measuring the density and strength parameters within the acceptable limits. 31mixes were tried, out of which only 11 were selected for detailed evaluation of their hardened properties. The study of the hardened mechanical, durability and thermal properties was conducted in the third stage.

The following sections of this Chapter serve to explain the experimental program covering the three main stages explained earlier.

3.2 Materials used in the development of SLWC mixes

3.2.1 Cement

The cement type used was ASTM C 150 Type I, having a specific gravity of 3.15. This is the most commonly used cement type in the Kingdom. The cement used was stored safely to avoid moisture exposure problems. Its chemical composition is shown in Table 3.1.

Table 3.1: Chemical composition of cement.

Constituent	Weight %
SiO_2	20.52
Fe_2O_3	3.8
Al_2O_3	5.64
CaO	64.35
MgO	2.11
Na_2O	0.19
K_2O	0.36
SO_3	2.1
Loss on ignition	0.7
Alkalis (Na_2O+0.658 K_2O)	0.43
C_3S	56.7
C_2S	16.05
C_3A	8.52
C_4AF	11.56

3.2.2 Aggregates

3.2.2.1 Fine Aggregate

Dune sand, a vastly available material in the Kingdom, was used as fine aggregate in this study. The specific gravity of fine aggregate was 2.56, and the water absorption was 0.4-0.6%. Table 3.2 shows the grading of the dune sand used in the study.

Table 3.2: Grading of the fine aggregate used in the study

ASTM Sieve #	Size (mm)	% passing
4	4.75	100
8	2.36	100
16	1.18	100
30	0.600	76
50	0.300	10
100	0.0150	4

3.2.2.2 Coarse Aggregate

In this study the coarse aggregates used were crushed limestone sourced from a local quarry in Abu Hadriah, Eastern Province of Saudi Arabia. The coarse aggregate has a maximum aggregate size of 12.5 mm, specific gravity of 2.60and absorption of 1.4%. Four sizes of coarse aggregates were used in this study are 12.5 mm (½ inch), 9.5 mm (3/8 inch), 4.75 mm (3/16 inch), and 2.36 mm (3/32 inch). The physical properties of limestone are shown in Table 3.3.

Table 3.3: Physical properties of limestone aggregate.

Aggregate type	Limestone
Specific gravity	2.6
Absorption (%)	1.1-1.4
Fineness Modulus	3.23
Unit weight(kg/m^3)	1845

The chemical constituents of limestone aggregate are given in Table 3.4. And additional properties are shown in Table 3.5.

Table 3.4: Chemical composition of limestone aggregate.

Constituent	Weight %
CaO	54.97
SiO_2	0.01
Al_2O_3	0.17
Fe_2O_3	0.05
SiO_2+Al_2O_3+Fe_2O_3 (>=70)	0.23
MgO	0.64
Loss on ignition	43.66

Table 3.5: Additional properties of limestone aggregate.

Material finer than ASTM # 200 Sieve	0.32%
Loss on Abrasion	23.50%
Clay lumps and friable particles	0.45%
Mineralogical Composition	
$CaCO_3$	80%
SiO_2	20%

3.2.2.3 Light weight Aggregates

3.2.2.3.1 Expanded Perlite Aggregates

The expanded perlite aggregate used is specially graded confirming to ASTM C-332-1989 Group I. It is produced largely in the kingdom of Saudi Arabia in many factories such as SAUDI PERLITE INDUSTRIES and ARABIAN VERMICULITE INDUSTRIES. The expanded perlite has a specific gravity of 0.355 and water absorption of 75%. The chemical composition of the perlite is given in Table 3.6.And its grading is given in Table 3.7.

Table 3.6: Chemical composition of the perlite aggregate.

Typical Analysis	
Silicon	33.8
Aluminum	7.2
Potassium	3.5
Sodium	3.4
Iron	0.6
Calcium	0.6
Magnesium	0.2
Trace	0.2
Oxygen (by difference)	47.5
Net Total	97
Bound Water	3. 0
Total	100

Table 3.7: Grading of the perlite aggregate used in the study.

Sieve Size	Spacing	Weight % Passing
No. 4	4.75 mm	100
No. 8	2.36 mm	85 - 1 00
No. 16	1.18 mm	40 - 85
No. 30	600 µm	20 - 60
No. 50	300 µm	5-25
No. 100	150 µm	0 - 10
DRY LOOSE WE IGHT (kg/m^3)		
Minimum		Maximum
60		150

3.2.2.3.2 Scoria

Scoria was brought from a quarry in AL-MADINA in western Saudi Arabia. The Physical properties of scoria are given in Table 3.8.

Table 3.8: Physical properties of scoria.

Property	Value
Specific gravity	1.5
Absorption (%)	22.2
Fineness Modulus	5.4
Unit weight(kg/m^3)	866

3.2.2.3.3 Polypropylene

Polypropylene beads were brought from SABIC (Saudi Basic Industries Corporation) company in Dammam. The polypropylene beads used has a specific gravity of 0.886 and water absorption of only 0.008%.

3.2.2.4 Industrial waste byproducts

3.2.2.4.1 Oil Ash

The oil ash (OA) used was brought from the Saudi Electricity Company power plant in Shayba, Saudi Arabia. It has a specific gravity of 0.6 and water absorption of 1.5%.Table 3.9 shows the chemical composition of the OA used.

Table 3.9: Chemical composition of Oil Ash.

Constituent	Weight %
SiO_2	1.65
CaO	0.45
Al_2O_3	< 0.10
Fe_2O_3	0.47
MgO	0.48
K_2O	0.03
Na_2O	0.53
V_2O_5	2.65
Sulfur	9.6
Na_2O + (0.658K_2O), %	0.55
Loss on ignition	60.6
Moisture %	5.9

3.2.2.4.2 Silica Fume (SF)

The silica fume used in this study was brought from a local ready mixed concrete company. The chemical properties are shown in Table 3.10.

Table 3.10: Chemical composition of the silica fume used in the study.

Constituent	Weight %
SiO_2	92.5
Al_2O_3	0.72
Fe_2O_3	0.96
CaO	0.48
MgO	1.78
SO_3	-
K_2O	0.84
Na_2O	0.5
Loss on ignition	1.55

3.2.3 Super plasticizer (SP)

The super plasticizer used in this study was Glenium 51®. It is a new generation poly carboxylic-based ether hyper plasticiser. It was brought from a local supplier in the Kingdom. The super plasticizer was used in various dosages to get the required slump (100 ± 25 mm). The dosages were between 0.5 % to 1.2 % of the weight of cement. The manufacturer technical data of the super plasticizer used is presented in Table 3.11.

Table 3.11: Technical data of Glenium 51®.

Appearance	Brown liquid
Specific gravity @ 20°C	1.08±0.02 g/cm^3
pH-value @ 20°C	7.0±1.0
Alkali content	≤ 5.0
Chloride content	≤ 0.1 %

3.2.4 Mixing water

The normal sweet water in the laboratory tap was used in the preparation of the trial mixtures and curing.

3.3 SLWC trial mixes

Many trial mixes were designed, investigated and tested before choosing it for detailed experimental program. The perlite was the major component, in all mixes, because of its superior thermal insulating property needed in this research. OA and SF were considered as fine aggregate, in most of the trial mixtures; because they have a specific gravity less than sand to give lighter concrete in addition to improve the mechanical, durability and thermal properties.

3.3.1 SLWC Trial Mix Design

The design of the trial mixes was made by using the absolute volume method.The cement content and w/c was chosen, and the proportion of all normal weight and light weight aggregate was assumed in a percentage of total aggregate. The mass of total aggregate is solved using the absolute volume equation, and then the masses of the different aggregate were obtained. The analytical derivation of the aggregate masses is given as follows:

Consider the absolute volume equation represented by

$$V_{TA} + \sum_i V_i = 1 \quad \text{………} (1)$$

Where $V_i$is the volume of individual components excluding the aggregates. Those components are cement, mineral admixtures, and water. Equation (1) can be rewritten as

$$V_{TA} + \sum_i \frac{m_i}{\rho_i} = 1 \text{………} (2)$$

In which m and $\rho$are the masses and densities of individual components. The cementing materials volumes are known for a mix. Also water volume is known from the w/c. The only unknowns are the aggregate volume. Thus,

$$V_{TA} = 1 - \sum_i \frac{m_i}{\rho_i} \text{………} (3)$$

Then the volume of total aggregate can be expressed in mass equation for the individual aggregate to find out its mass as follows:

$$V_{TA} = \frac{m_{Limestone}}{\rho_{Limestone}} + \frac{m_{Sand}}{\rho_{Sand}} + \frac{m_{Perlite}}{\rho_{Perlite}} + \frac{m_{Scoria}}{\rho_{Scoria}} + \frac{m_{polypropylene}}{\rho_{polypropylene}} + \frac{m_{oilash}}{\rho_{oilash}} + \frac{m_{silicafume}}{\rho_{silicafume}} \quad (4)$$

From this expression, and having assumed the percentages of each individual aggregate of total aggregate, the total aggregate mass can be obtained by substituting Equation (4) in(3).and the individual aggregates masses can be obtained.

The total water of the mix is corrected by adding the absorbed water for each type of aggregate used in the mix.

Table 3.12 illustrates the details of the trial mixes. Some abbreviations of the material used in Table 3.12 as follows:

SF: Silica Fume; OA: Oil Ash; w/c: water cement ratio; PRT: Expanded Perlite Aggregate; LSA: Limestone Aggregate; SA: Sand; PP: Polypropylene; SC:Scoria Aggregate.

Table 3.12: Details of trial mixtures.

#	Description of mix	Ingredients										
		Cement kg/m^3	SF kg/m^3	OA kg/m^3	w/c	PRT/ TA	LSA/ TA	SA/ TA	PP/ TA	SC/ TA	SF/ TA	OA/ TA
1	20% Perlite total aggregates.	400	0	0	0.35	0.2	0.4	0.4	0	0	0	0
2	20% Perlite, and 20% Scoria of total aggregates.	400	0	0	0.35	0.2	0.2	0.4	0	0.2	0	0
3	20% Perlite, and 26% Scoria of total aggregates.	400	0	0	0.35	0.2	0.14	0.4	0	0.26	0	0
4	20% Perlite,and 14% polypropylene of total aggregates.	400	0	0	0.35	0.2	0.26	0.4	0.14	0	0	0
5	20% Perlite, and 10% oil Ash of total aggregates.	400	0	0	0.35	0.2	0..4	0.3	0	0	0	0.1
6	30% Perlite of totalaggregates and 10% silica fume replacing cement and w/c 0.325.	360	40	0	0.325	0.3	0.3	0.4	0	0	0	0
7	30% Perlite, and 17.5% Scoria of total aggregates.	400	0	0	0.35	0.3	0.175	0.35	0	0.175	0	0
8	15% Perlite, and 15% polypropylene of total aggregate and w/c 0.4.	400	0	0	0.4	0.15	0.3	0.4	0.15	0	0	0
9	15% Perlite, and 15% polypropylene of total aggregate and w/c 0.35.	400	0	0	0.35	0.15	0.3	0.4	0.15	0	0	0
10	15% Perlite of total aggregates and 10% silica fume replacing cement.	360	40	0	0.35	0.15	0.4	0.45	0	0	0	0
11	Cement content 350 kg/m3, 15% Perlite of total aggregates, and 10% silica fume replacing cement.	315	35	0	0.35	0.15	0.4	0.45	0	0	0	0
12	15% Perlite,20%Scoria of total aggregates, and 10%OA replacing sand.	400	0	0	0.4	0.15	0.25	0.3	0	0.2	0	0.1
13	10% Perlite, 25% Scoria of total aggregates, and 10%OA replacing sand.	400	0	0	0.4	0.1	0.25	0.3	0	0.25	0	0.1
14	15% Perlite, and 20%Scoria of total aggregates	400	0	0	0.4	0.15	0.25	0.4	0	0.2	0	0
15	10% Perlite and 25%Scoria of total aggregates	400	0	0	0.4	0.1	0.25	0.4	0	0.25	0	0
16	15% Perlite, 10%polypropylene of total aggregates,and 10%OA replacing sand.	400	0	0	0.4	0.15	0.35	0.3	0.1	0	0	0.1
17	10% Perlite, 15%polypropylene of total aggregates, and 10%OA replacing sand.	400	0	0	0.4	0.1	0.35	0.3	0.15	0	0	0.1
18	15% Perlite and 10%polypropylene of total aggregates.	400	0	0	0.4	0.15	0.35	0.4	0.1	0	0	0
19	Using 10% Perlite and 15%polypropylene of total aggregates.	400	0	0	0.4	0.1	0.35	0.4	0.15	0	0	0

Table 3.12: (Continued).

#	Description of mix	Ingredients										
		Cement kg/m^3	SF kg/m^3	OA kg/m^3	w/c	PRT/TA	LSA/TA	SA/TA	PP/TA	SC/TA	SF/TA	OA/TA
20	15% Perlite, 20%Scoria of total aggregates, and 10%SF as a filler aggregate.	400	0	0	0.4	0.15	0.25	0.3	0	0.2	0.1	0
21	Using 10% Perlite, 25%Scoria of total aggregates, and 10%SF as a filler aggregate.	400	0	0	0.4	0.1	0.25	0.3	0	0.25	0.1	0
22	Using 15% Perlite, 10%Polypropylene of total aggregates, and 10%SF as a filler aggregate.	400	0	0	0.4	0.15	0.35	0.3	0.1	0	0.1	0
23	10% Perlite, 15%Polypropylene of total aggregates, and 10%SF as a filler aggregate.	400	0	0	0.4	0.1	0.35	0.3	0.15	0	0.1	0
24	10% Perlite, 5%Polypropylene of total aggregates, and 10%SF as a filler aggregate.	400	0	0	0.4	0.1	0.35	0.4	0.05	0	0.1	0
25	10% Perlite, 5%Polypropylene f total aggregates, and 5%SF as a filler aggregate.	400	0	0	0.4	0.1	0.4	0.4	0.05	0	0.05	0
26	10% Perlite and 5%Polypropylene f total aggregates	400	0	0	0.4	0.1	0.45	0.4	0.05	0	0	0
27	10% Perlite, 25%Scoria of total aggregates, and 5%SF as a filler aggregate.	400	0	0	0.4	0.1	0.3	0.3	0	0.25	0.05	0
28	12.5% Perlite of total aggregates and 2.5%OA as filler aggregate.	400	0	0	0.4	0.125	0.45	0.4	0	0	0	0.025
29	10% Perlite, 20%Scoria of total aggregates, and 2.5%OA as a filler aggregate.	400	0	0	0.4	0.1	0.3	0.375	0	0.2	0	0.025
30	7.5% Perlite, 52.5%Scoria of total aggregates, and 2.5%OA as a filler aggregate.	400	0	0	0.4	0.075	0	0.375	0	0.525	0	0.025
31	7.5% Perlite, 52.5%Scoria of total aggregates, and 2.5%OA as a filler aggregate.	400	0	0	0.4	0.075	0.275	0.35	0	0.25	0	0.05
32	10% Perlite, 30%Scoria of total aggregates, and 2.5%SF as a filler aggregate.	400	0	0	0.4	0.1	0.2	0.375	0	0.3	0.025	0

The optimum trial mixes were selected bases on the 7-days compressive strength and unit weight results. Mixtures exhibiting low unit weight and high compressive strength were selected for the detailed evaluation (experimental) program. Eleven concrete mixes were selected (M17, M21, M23, M24, M25, M27, M28, M29, M30, M31, and M32), and specimens were prepared to evaluate the hardened properties. Cement content was 400 kg/m^3 and w/c ratio was 0.4 in all the chosen mixes.

3.4 Preparation of SLWC Specimens

The SLWC specimens was poured and cured to carry out different tests planned in this research. The procedure of casting specimens, after initially sieving the aggregates to obtain the required sizes, is described as follows: First the weight of dry component were measured and added together in laboratory electric revolving drum mixer of 0.7 m^3. The dry components were mixing for 2-3 minutes, and then about half of the water was added while the drum was still rotating until all particles have become wet. Measured quantity of super plasticizer was added gradually to the remaining water that was added to the mix. The mixture was kept running for about 20±5 minutes until uniform consistency was obtained.

Then the mixed concrete was poured in the moulds of required sizes and shapes. The specimens were vibrated until complete consolidation and a thin mortar film appeared on the surface of concrete. The specimens were covered, after casting, with plastic sheet for 24 hours in the laboratory environment (22 ± 30 $^{\circ}C$) to reduce loss of mix water. After 24 hours, the specimens were de-molded and placed in a curing tank till the time of test. Table 3.13 shows the type and number of specimens prepared.

Table 3.13: Type and number of specimens prepared.

#	Property	Specimen shape	Dimensions (mm)	Test Standard	Number of specimens prepared
1	Compressive strength	Cube	100x100 x100	ASTM C 39	99
2	Drying shrinkage	Prism	50x50x250	ASTM C 157	33
3	Corrosion potentials	Cylinder	75x150	ASTM C 876	33
4	Corrosion current density	Cylinder	75x150	LPRM	33
5	Chloride permeability	Cylinder	100x50	ASTM C 1202	33
6	Water absorption	Cylinder	75x150	ASTM C 642	33
7	Thermal conductivity	Slab	350x350x50	ASTM C 201	11
8	Flexural strength	Prism	50x50x250	ASTM C 78	33

3.5 Testing:

The SLWC specimens were tested for the following properties:

3.5.1 Compressive Strength

The compressive strength was determined according to ASTM C 39 [16] after 7, 14, and 28 days of curing in water. The size of the concrete specimens was 100 mm × 100 mm × 100 mm. A hydraulic type automatic compression machine was used in the test; the machine is illustrated in Figure 3.1.

Compression load was applied at a rate of 2.33 kN/s until the failure of the specimen. The compressive strength of the specimen was recorded from the machine display screen.

Figure 3.1: Matest® hydraulic type compressive strength testing machine.

3.5.2 Drying Shrinkage

The loss of water evaporated from the freshly hardened concrete when it is exposed to air reduces the volume of concrete and causes shrinkage. Shrinkage leads to cracking of restrained members of concrete. The drying shrinkage was determined according to ASTM C157 [17].The size of specimens was 50x50x250 mm, each specimen was tested using shrinkage measuring machine illustrated in Figure 3.2.The machine setup contains a stand fitted with a LVDT and connected to data logger. The drying shrinkage was monitored every 3 days in the first two weeks, and then every week in the following month then every 2 weeks for a period of three months. The shrinkage specimens are shown in Figure 3.3.

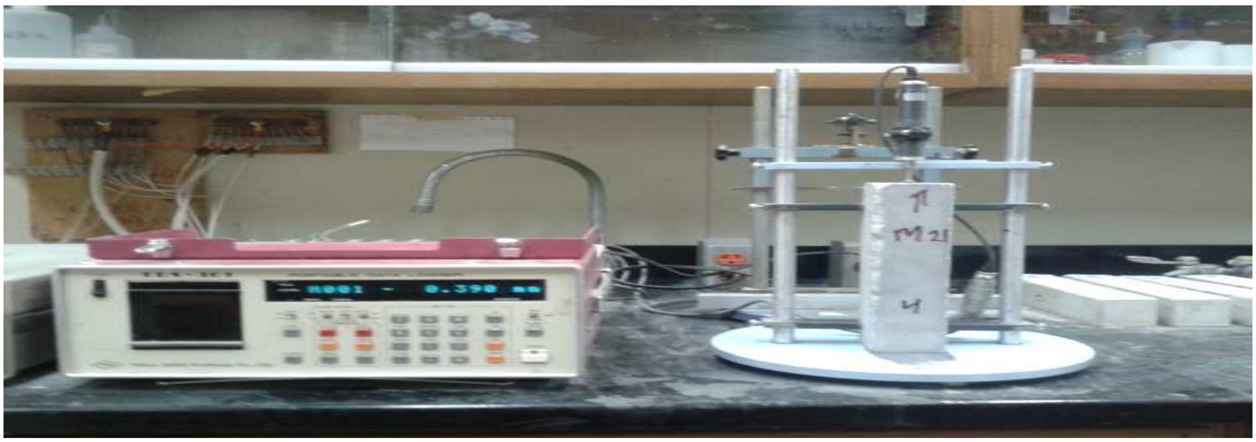


Figure 3.2: Setup for measuring drying shrinkage.

Figure 3.3: Drying shrinkage test specimens.

3.5.3 Reinforcement corrosion

SLWC specimens were exposed to 5% sodium chloride solution to measure the corrosion resistance .The specimen has a diameter of 75mm and height of 150mm and it was reinforced with a 12mm steel bar in the center. And a bottom cover of 25 mm. An epoxy coating over a layer of cement paste was applied at the concrete air interface and bottom to prevent service corrosion. Typical reinforced concrete specimen used in the measuring of the corrosion resistance is shown in Figure 3.4.

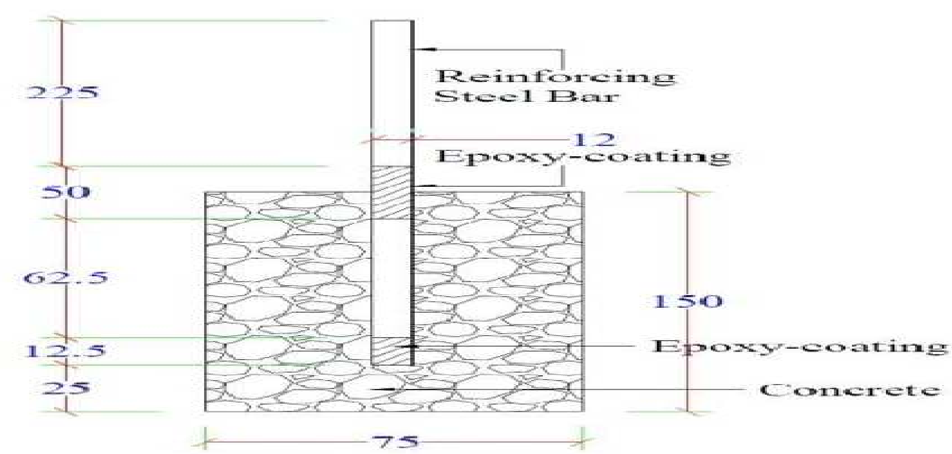


Figure 3.4: Schematic of corrosion test specimen (Dimensions in mm).

Reinforcement corrosion was determined by monitoring the corrosion potentials according to ASTM C876 [22], and the corrosion current density by using linear polarization resistance method (LPRM) [23].

3.5.3.1 Corrosion potentials

The corrosion potentials were measured using a saturated calomel reference electrode (SCE). The positive terminal of a high impedance digital voltmeter was connected to the electrical lead from the reference electrode while the negative terminal was connected to the steel bar from the concrete specimen. The corrosion potential measurement setup is shown in Figure 3.5.

Figure 3.5: Corrosion potential test setup.

3.5.3.2 Corrosion current density

The resistance to polarization was measured by the three electrode method using a Potentiostat/Galvanostat. The working electrode terminal was connected to the steel rod and the counter and reference electrode terminals of the Potentiostat/Galvanostat were connected to a steel plate and a reference electrode, respectively. The corrosion current density test setup is shown in Figure 3.6.

The steel was polarized to ± 10 mV of the corrosion potential at a rate of 3 mV/min and the resulting current between the working and current electrode was measured. The slope of the current-potential curve gives the Rp value. Corrosion current density (Icorr) was evaluated using the following relationship:

$$Icorr \ = \frac{B}{Rp}$$

Where:

$Icorr$ = Corrosion current density, μA/cm^2.

Rp = Resistance to polarization, $\Delta E/\Delta I$, Ω.cm^2.

$B = \frac{\beta a \ X \ \beta c}{2.3(\beta a + \beta c)}$

Ba and βc are the anodic and cathodic Tafel constants, mV/decade, respectively.

Figure 3.6: Corrosion current density test setup.

The Tafel constants are normally obtained by polarizing the steel to ± 250 mV of the corrosion potential (Tafel plot). However, in the absence of sufficient data on βa and βc, a value of B equal to 26 mV for steel in active condition and 52 mV for steel in passive condition is often used [29]. Lambert et al. [30] have reported a good correlation between corrosion rates determined using these values and the gravimetric weight loss method.

3.5.4 Chloride permeability

Rapid chloride permeability procedure was used to determine the chloride permeability according to ASTM C1202 [21]. This method basically determines the electrical conductance of concrete in which the charge carrying species is chloride ion via the pores of the concrete.

A concrete disk of 50 mm thickness was cut from a sample of 100 mm x200 mm cylindrical specimen. An Epoxy coating was applied on the curved surface; the specimen was kept in vacuum desiccators for 4 hours, and later in water for about 18 hours.

Following the 18 hours of saturation, the disks were fixed between two half cells, one filled with 3% NaCl solution (w/w) and the other with 0.3N NaOH solution. An automatic computerized testing machine was used for the test. A potential difference of 60 V DC was maintained across each cell holding the specimens, and the current flowing through each one was recorded at intervals of 30 minutes by the computer, via the testing machine. The total charge passed, in Coulombs was recorded over a six hour period. The test was performed at a room temperature of 25°C. The machine handles all the relevant calculations contained in ASTM C1202 including correction for disk diameter. The final adjusted total charge was read and recorded from the computer. Figure 3.7 shows the test set-up.

Figure 3.7: Rapid chloride permeability test setup.

3.5.5 Water absorption

The air voids inside the concrete specimens affect the concrete durability as they become a source of penetration of aggressive agent such as chloride, sulfate, etc. In normal concrete voids are generated due to water loss after hydration, moreover in lightweight concrete the light weight aggregates themselves contain voids that may affect the concrete durability. Thus, water absorption test was performed.

Water absorption test was conducted according to ASTM C 642 [19].The test specimen was a 75 mm diameter and 150 mm high cylindrical concrete specimens. The specimens were cured for 28 days, then the specimens were dried in an oven for 24 hours at a temperature of 110 ^{0}C and then their weights were recorded. Then the specimens were immersed in water for 48 hours and the saturated surface dry weights were measured. The following equation was used to calculate the water absorption of the specimens:

Saturated surface dried sample weight = A

Oven dried sample weight = B

Water absorption = $\frac{A-B}{B}$ x 100%

The average water absorption value of three specimens was taken for each sample. Figure 3.8 illustrates the specimens utilized for water absorption.

a) Dried Specimens

(b) Immersed Specimens

Figure 3.8: Water absorption specimens.

3.5.6 Thermal conductivity

The thermal conductivity test was conducted according to ASTM Standard C 201 [20]. The thermal conductivity was measured using a guarded hot plate under steady-state conditions. The specimens had dimensions of 35cm x 35cm x 5 cm. The specimens were dried in oven at 70 °c to remove the moisture. Figure 3.9shows a typical specimen used to determine the thermal conductivity.

Figure 3.9: Specimen used for thermal conductivity measurements.

The thermal conductivity of the SLWC was measured using The Dynatech guarded hot plate thermal conductance measuring system, TCFG-R4-6. The system is illustrated in Figure 3.10.

Figure 3.10: Dynatech guarded hot plate thermal conductivity measuring system.

The schematic of Dynatech guarded hot plate thermal conductance measuring system, TCFG-R4-6, is presented in Figure 3.11.

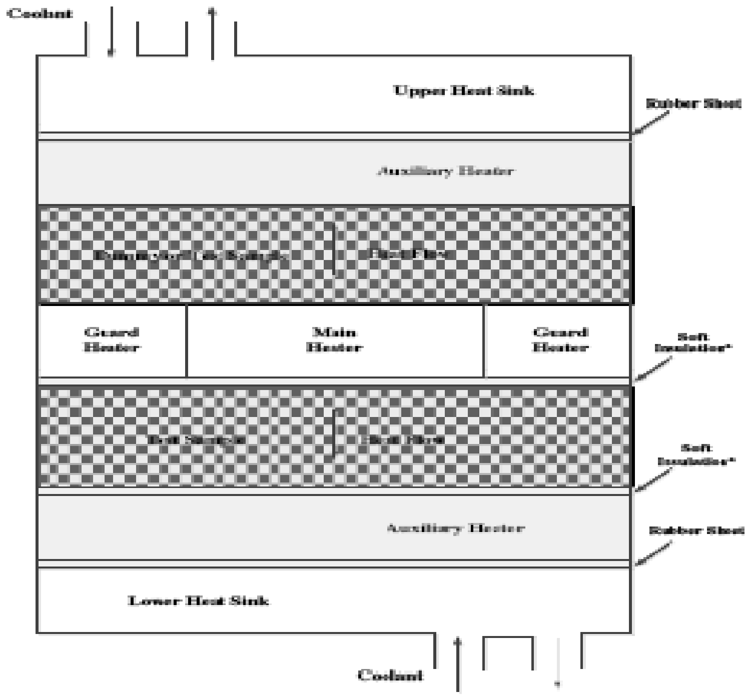


Figure 3.11: Graphical Diagram of Dynatech guarded hot plate thermal conductance measuring system.

The test device accuracy, in the thermal conductivity value, for a sample of maximum thickness of 15 cm is ± 4% under steady state conditions.

A Styrofoam sheet was used to fix the sample dimension to the test device dimensions of 61 cm x 61 cm. The thermocouples were connected to a five point in the bottom and top surface and thermocol sheet was wrapped inside a piece of soft, thick cloth as illustrated in Figure 3.12.

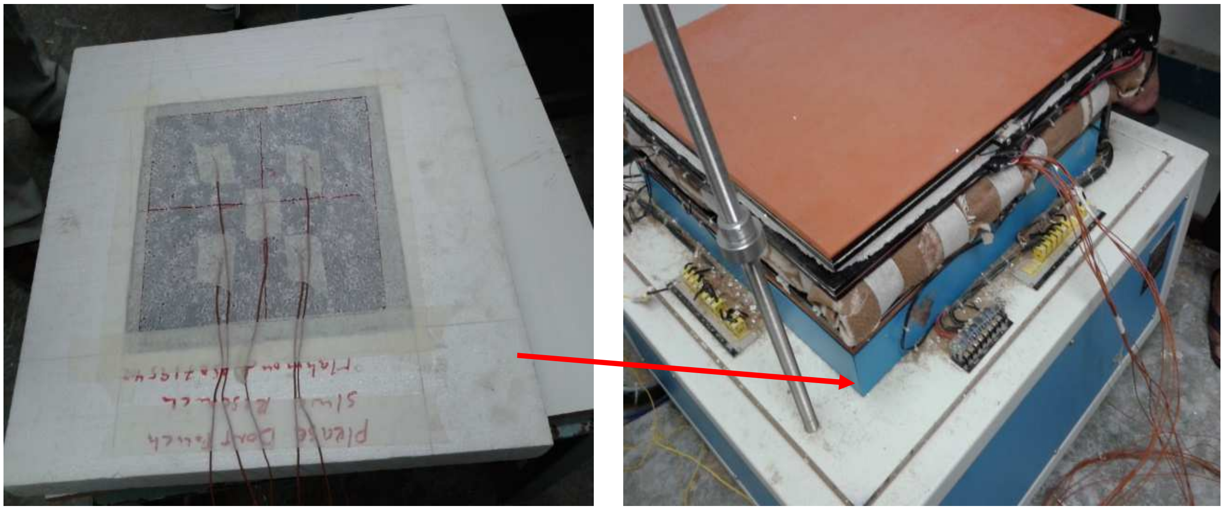


Figure 3.12: Thermal conductivity test specimen preparation.

The thermal conductivity was conducted on the 11 selected mixes specimens. The illustration of the complete thermal conductivity setup is presented in Figure 3.13.

Figure 3.13: Thermal conductivity setup.

3.5.7 Flexural strength

The most used test to measure the flexural strength of concrete is the standard three point loading test. The test was conducted according to ASTM C 78 [18] to obtain the modulus of rupture (MOR). The illustration of the test setup is presented in Figure 3.14.

Figure 3.14: Flexural strength test Setup

The test specimen dimensions were 25 cm x 5 cm x 5 cm. The third-point loading flexural test illustration is presented in Figure 3.15.

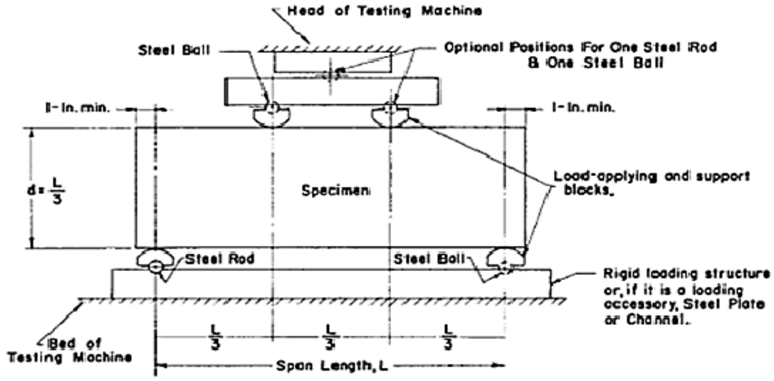


Figure 3.15: The third-point loading flexural test.

The maximum load and maximum deflection recorded at the failure of the specimen, as illustrated in Figure 3.16, and the modulus of rupture was calculated as follows:

$R = PL/bd^2$

Where:

R = modulus of rupture, psi, or MPa.

P = maximum applied load indicated by the testing machine, lbf, or N.

L = span length, in., or mm.

b = average width of specimen, in., or mm, at the fracture.

d = average depth of specimen, in., or mm, at the fracture.

Figure 3.16: Flexural failure of the specimen.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the mechanical, durability, and thermal conductivity of the developed SLWC prepared with a combination of normal and lightweight aggregate, constant cement content of 400 kg/m^3, and constant w/c ratio of 0.4.The expanded perlite aggregate is a major component in all mixes.

The mix constituents in the 11 selected mixes are described in Table 4.1, and each mix was given an ID for the comfort of result illustration. Some abbreviations used in the table as follows:

SF: Silica Fume; OA: Oil Ash; w/c: water cement ratio; PRT: Expanded Perlite Aggregate; LSA: Limestone Aggregate; SA: Sand; PP: Polypropylene; SC:Scoria Aggregate.

Table 4.1: Description of the selected mixes.

#	Mix #	Description of mix	Mix ID
1	M17	10% Perlite, 15% polypropylene, and 10% Oil Ash of total aggregates.	M17 (10PER-15PP-10OA)
2	M21	10% Perlite, 25% Scoria, and 10% Silica Fume of total aggregates.	M21 (10PER-25SC-10SF)
3	M23	10% Perlite, 15% Polypropylene, and 10% Silica Fume of total aggregates.	M23 (10PER-15PP-10SF)
4	M24	10% Perlite, 5% Polypropylene, and 10% Silica Fume of total aggregates.	M24 (10PER-5PP-10SF)
5	M25	10% Perlite, 5% polypropylene, and 5% Silica Fume of total aggregates.	M25 (10PER-5PP-5SF)
6	M27	10% Perlite, 25% Scoria, and 5% Silica Fume of total aggregates.	M27 (10PER-25SC-5SF)
7	M28	12.5% Perlite, and 2.5% Oil Ash of total aggregates.	M28 (12.5PER-2.5OA)
8	M29	10% perlite, 20% Scoria, and 2.5% Oil Ash of total aggregates.	M29 (10PER-20SC-2.5OA)
9	M30	7.5% Perlite, 52.5% Scoria, and 2.5% Oil Ash of total aggregates.	M30 (7.5PER-52.5SC-2.5OA)
10	M31	7.5% Perlite, 25%Scoria, and 5% Oil Ash of total aggregates.	M31 (7.5PER-25SC-5OA)
11	M32	10% Perlite, 30%Scoria, and 2.5% Silica Fume of total aggregates.	M32 (10PER-30SC-2.5SF)

4.2 Unit Weight

The 28-day average unit weight, according to ASTM standard [15], of SLWC specimens is presented in Table 4.2 and is plotted in Figure 4.1.

Table 4.2: Average 28-days unit weight.

Mix #	Description of mix	Mix ID	Average 28- day Unit Weight Kg/m^3
M17	10% Perlite, 15% polypropylene, and 10% Oil Ash of total aggregates.	M17 (10PER-15PP-10OA)	1702.86
M21	10% Perlite, 25% Scoria and 10% Silica Fume of total aggregates	M21 (10PER-25SC-10SF)	1854.11
M23	10% Perlite, 15% Polypropylene, and 10% Silica Fume of total aggregates.	M23 (10PER-15PP-10SF)	1674.27
M24	10% Perlite, 5% Polypropylene, and 10% Silica Fume of total aggregates.	M24 (10PER-5PP-10SF)	1720.15
M25	10% Perlite, 5% polypropylene, and 5% Silica Fume of total aggregates.	M25 (10PER-5PP-5SF)	1785.54
M27	10% Perlite, 25% Scoria, and 5% Silica Fume of total aggregates.	M27 (10PER-25SC-5SF)	1836.11
M28	12.5% Perlite, and 2.5% Oil Ash of total aggregates.	M28 (12.5PER-2.5OA)	1771.32
M29	10% perlite, 20% Scoria, and 2.5% Oil Ash of total aggregates.	M29 (10PER-20SC-2.5OA)	1833.82
M30	7.5% Perlite, 52.5% Scoria, and 2.5% Oil Ash of total aggregates.	M30 (7.5PER-52.5SC-2.5OA)	1830.18
M31	7.5% Perlite, 25%Scoria, and 5% Oil Ash of total aggregates.	M31 (7.5PER-25SC-5OA)	1890.51
M32	10% Perlite, 30%Scoria, and 2.5% Silica Fume of total aggregates.	M32 (10PER-30SC-2.5SF)	1847.76

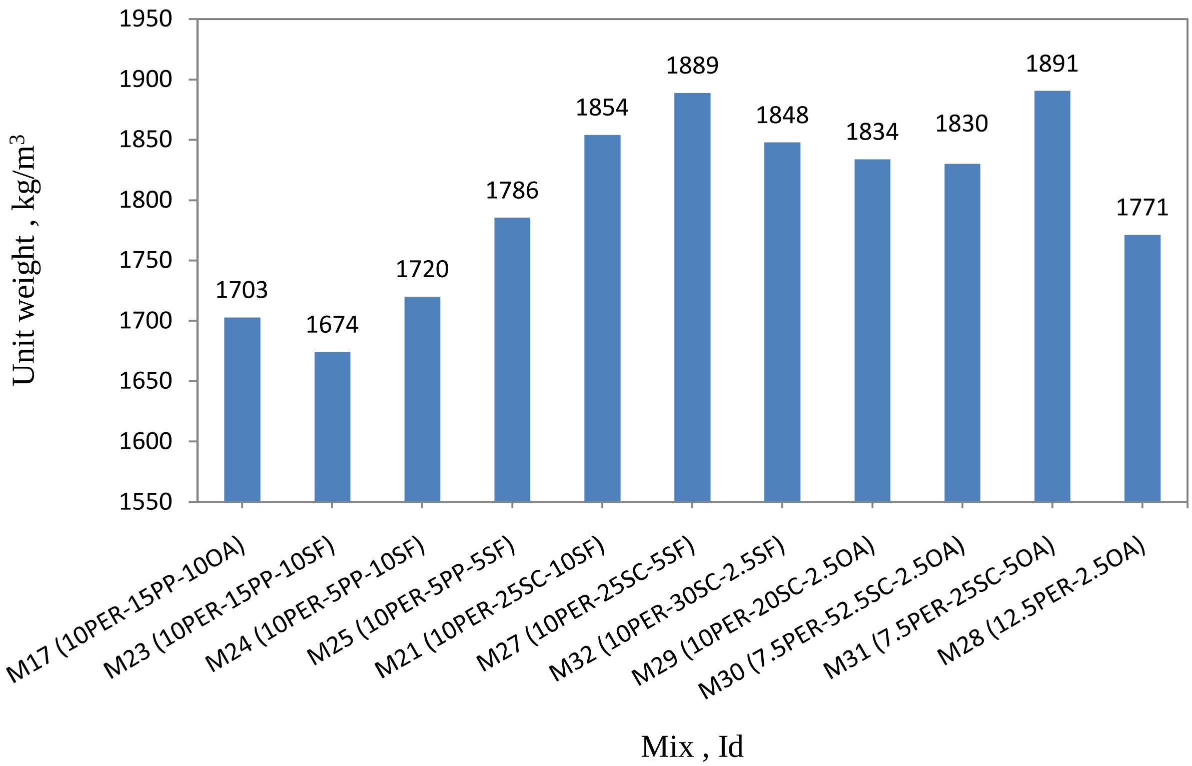


Figure 4.1: Average 28-day unit weight.

The unit weight was in the rangeof1674 kg/m^3 to 1891 kg/m^3 and it satisfies the requirement of structural lightweight concrete [2]. Mixes containing polypropylene (M17, M23, M24, and M25) were in the lowest unit weight range from 1674 to 1785 kg/m^3.The lowest unit weight of 1674 kg/m^3 was in the mix with the highest percentage of polypropylene (M23). The unit weight of mixes containing Scoria (M21, M27, and M29-M32) was in the range of 1830 to 1891kg/m^3. The highest unit weight of 1891 kg/m^3 measured in the mix containing scoria and lowest percentage of perlite of 7.5%; this indicate the effect of Perlite in reducing the unit weight.

4.3 Compressive Strength

The average 7, 14, and 28 compressive strength of SLWC specimens is presented in Table 4.3 and is plotted in Figure 4.2.

Table 4.3: Average Compressive strength after 7, 14, and 28 days of curing.

Mix #	Description of mix	Mix ID	Average Compressive Strength,MPa		
			7 days	14 days	28 days
M17	10% Perlite, 15% polypropylene, and 10% Oil Ash of total aggregates.	M17 (10PER-15PP-10OA)	N/A	14.8	22.2
M21	10% Perlite, 25% Scoria, and 10% Silica Fume of total aggregates.	M21 (10PER-25SC-10SF)	30.1	32.0	35.4
M23	10% Perlite, 15% Polypropylene, and 10% Silica Fume of total aggregates.	M23 (10PER-15PP-10SF)	15.7	17.8	21.3
M24	10% Perlite, 5% Polypropylene, and 10% Silica Fume of total aggregates.	M24 (10PER-5PP-10SF)	19.7	22.3	25.8
M25	10% Perlite, 5% polypropylene, and 5% Silica Fume of total aggregates.	M25 (10PER-5PP-5SF)	16.3	21.2	25.4
M27	10% Perlite, 25% Scoria, and 5% Silica Fume of total aggregates.	M27 (10PER-25SC-5SF)	22.8	28.5	31.6
M28	12.5% Perlite, and 2.5% Oil Ash of total aggregates.	M28 (12.5PER-2.5OA)	14.1	15.9	19.7
M29	10% perlite, 20% Scoria, and 2.5% Oil Ash of total aggregates.	M29 (10PER-20SC-2.5OA)	17.3	19.3	21.0
M30	7.5% Perlite, 52.5% Scoria, and 2.5% Oil Ash of total aggregates.	M30 (7.5PER-52.5SC-2.5OA)	21.9	24.8	27.1
M31	7.5% Perlite, 25%Scoria, and 5% Oil Ash of total aggregates.	M31 (7.5PER-25SC-5OA)	23.2	25.6	29.2
M32	10% Perlite, 30%Scoria, and 2.5% Silica Fume of total aggregates.	M32 (10PER-30SC-2.5SF)	23.1	26.1	28.9

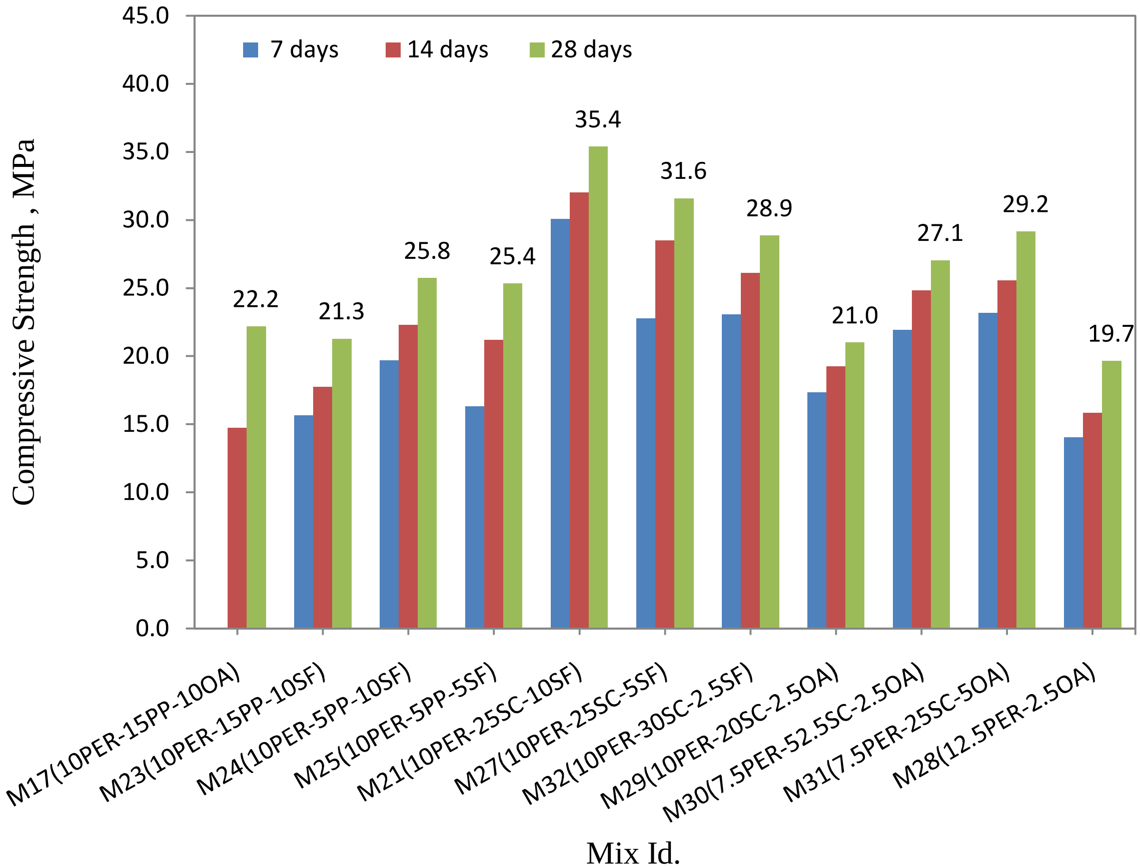


Figure 4.2: Average compressive strength after 7, 14, and 28 days of curing.

The 28 days compressive strength for all mixes has improved considerably from the 7, and 14 days compressive strength. The best improvement in the first 7 days was 30% in mix (M25) and in the second two weeks was 50% in mix (M17) that contains the highest percentage of oil ash that reduces the pores of the concrete. The overall best improvement was in mix (M25) about 55% that has 5% silica fume.

The highest 28-day compressive strength value of 35.4 MPa was recorded in mix (M21) that contains scoria and highest percentage of silica fume. The lowest 28-day compressive strength value of 19.7MPa was recorded in mix (M28) which has the highest percentage of Perlite (12.5%).

The SLWC mixes will be divided into three major groups for better comparison and analysis of the 28-day compressive strength results which are: Mixes containing perlite and polypropylene, mixes containing perlite and scoria, and a mix containing perlite without scoria or polypropylene.

4.3.1 Mixes containing Perlite and Polypropylene (M17, M23-M25)

The 7, 14, and 28-day compressive strength development is presented in Figure 4.3 and 28-day compressive strength for each mix is plotted in Figure 4.4.

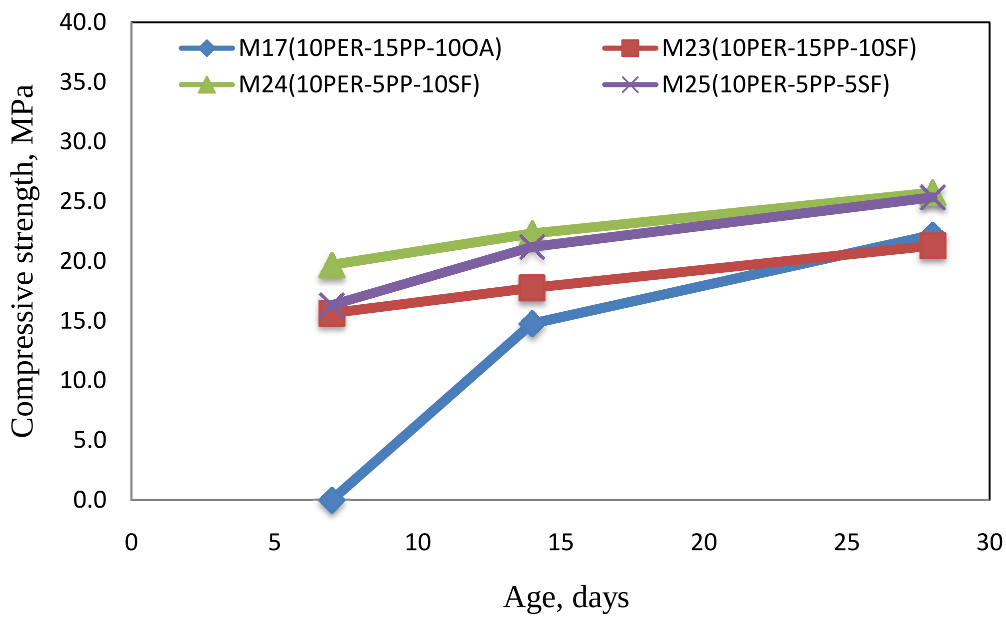


Figure 4.3: Compressive strength development for perlite and polypropylene mixes.

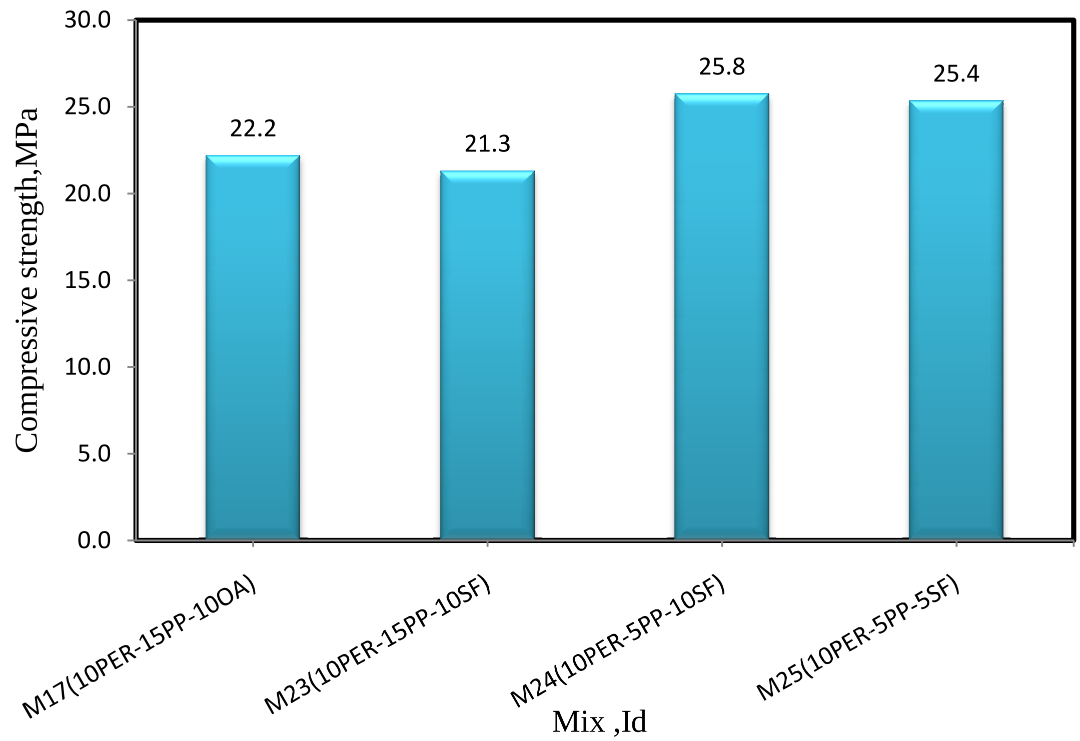


Figure 4.4: 28-day compressive strength of perlite and polypropylene mixes

The highest 28-days compressive strength in this group was 25.8 MPa measured in mix (M25) having lowest percentage of polypropylene 5% and 10% perlite with maximum silica fume (10%). The lowest 28-day compressive strength of21.3 MPa recorded in mix (M23) with the highest percentage of polypropylene used 15% and10% perlite with (10%) of silica fume.

In mix (M24) and (M25), the change of silica fume content from 10% to 5% of total aggregate, didn’t make a different in the 28-day compressive strength which was 25.8 and 25.4 MPa, respectively.

4.3.2 Mixes containing Perlite and Scoria (M21, M27, M29-M32)

The 7,14, and 28-day compressive strength in this group of mixes is presented in Figure 4.5 and 28-day compressive strength plotted in Figure 4.6.

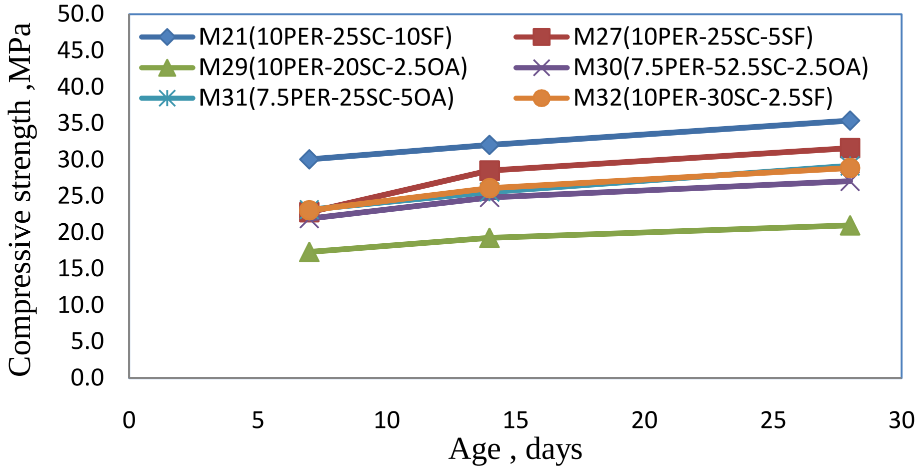


Figure 4.5: Compressive strength development for mixes with perlite and scoria.

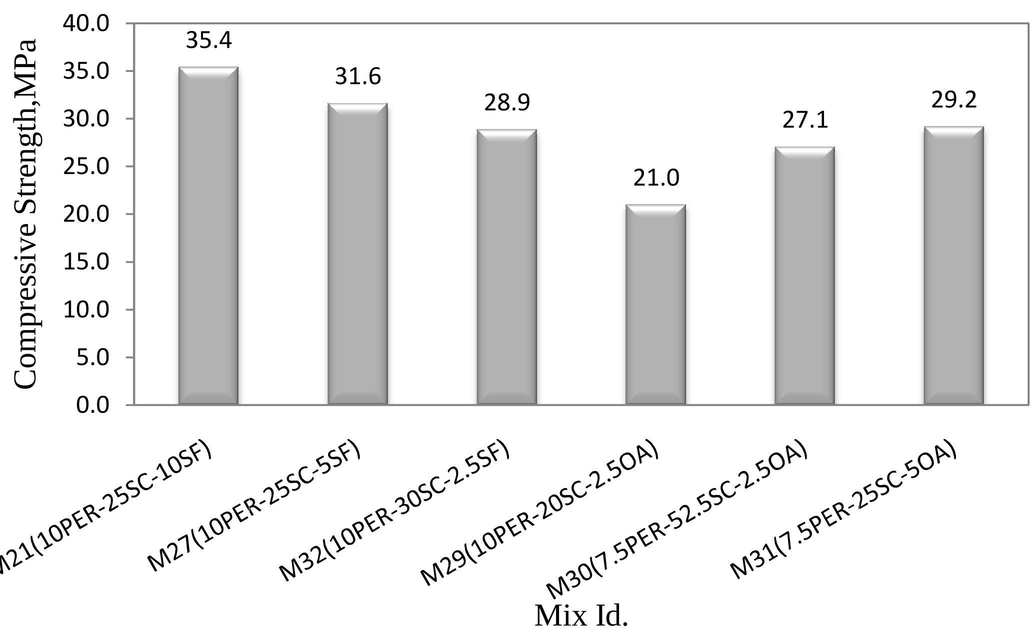


Figure 4.6: 28-day compressive strength for mixes with perlite and scoria.

The highest 28-day compressive strength in this group was 35.4 MPa measured in mix (M21) having 25% scoria, 10% perlite, and 10% silica fume. The lowest 28-day compressive strength is 21.0 MPa recorded in mix (M29) that having 20% of scoria, and 10% perlite with low percentage of oil ash (2.5%).

All mixes of Perlite, Scoria, and Silica fume combination are having a 28-day compressive strength more than 28.9 MPa, those are mixes (M21,M27, and M32) having a 28 days compressive strength of 35.4,31.6, and 28.9 MPa, respectively.

The two mixes with low percentage of perlite7.5% are giving high 28-day compressive strength of 27.1 and 29.2 MPa, respectively, for mixes M30 and M31.

4.3.3 Mix containing Perlite without Scoria and polypropylene (M 28)

This mix has the lowest 28-day compressive strength of 19.7 MPa because it contains the lowest percentage of perlite (12.5%). (See Figure 4.2)

It's obvious that the quantity of perlite shouldn't be more than 10% in order to obtain an acceptable compressive strength of SLWC.

4.4 Flexural Strength

The average modulus of rupture (MOR), failure load, and corresponding deflection of the SLWC specimens (250 x 50 x 50) is presented in Table 4.4.

Table 4.4: Average Modulus of rupture of the developed SLWC.

Mix #	Description of mix	Mix ID	Average failure Load, N	Average Deflection, mm	Modulus of Rupture, MPa
M17	10% Perlite, 15% polypropylene, and 10% Oil Ash of total aggregates.	M17 (10PER-15PP-10OA)	1624.9	0.6293	1.95
M21	10% Perlite, 25% Scoria, and 10% Silica Fume of total aggregates	M21 (10PER-25SC-10SF)	3035.0	0.6320	3.64
M23	10% Perlite, 15% Polypropylene, and 10% Silica Fume of total aggregates.	M23 (10PER-15PP-10SF)	1808.4	0.5544	2.17
M24	10% Perlite, 5% Polypropylene, and 10% Silica Fume of total aggregates.	M24 (10PER-5PP-10SF)	2888.2	0.5199	3.47
M25	10% Perlite, 5% polypropylene, and 5% Silica Fume of total aggregates.	M25 (10PER-5PP-5SF)	1949.9	0.5804	2.34
M27	10% Perlite, 25% Scoria, and 5% Silica Fume of total aggregates.	M27 (10PER-25SC-5SF)	3039.9	0.8015	3.65
M28	12.5% Perlite, and 2.5% Oil Ash of total aggregates.	M28 (12.5PER-2.5OA)	2568.3	0.7394	3.08
M29	10% perlite, 20% Scoria, and 2.5% Oil Ash of total aggregates.	M29 (10PER-20SC-2.5OA)	3268.1	0.5518	3.92
M30	7.5% Perlite, 52.5% Scoria, and 2.5% Oil Ash of total aggregates.	M30 (7.5PER-52.5SC-2.5OA)	2844.9	0.6263	3.41
M31	7.5% Perlite, 25%Scoria, and 5% Oil Ash of total aggregates.	M31 (7.5PER-25SC-5OA)	2911.5	0.5746	3.49
M32	10% Perlite, 30%Scoria, and 2.5% Silica Fume of total aggregates.	M32 (10PER-30SC-2.5SF)	2921.0	0.6492	3.51

The average modulus of rupture (MOR) of the developed SLWC is illustrated graphically in Figure 4.7.

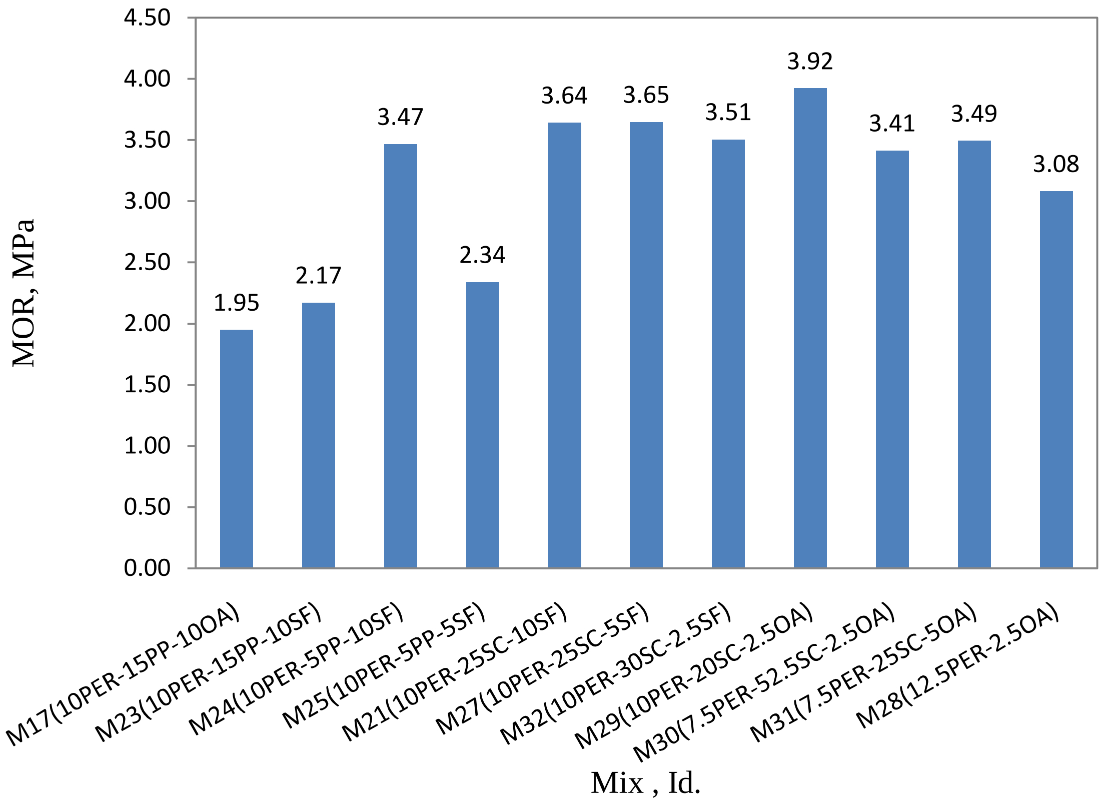


Figure 4.7: Average MOR of the developed SLWC.

The highest Modulus of rupture value of 3.92 MPa recorded in Mix (M29) that contains scoria and oil ash. The lowest Modulus of rupture of 1.95 MPa recorded in mix (M17) which has the highest percentage of polypropylene 15%. Mix M21 that has the highest compressive strength has the third highest value of MOR.

The modulus of rupture of the SLWC mixes will be discussed in the same groups that were used to discuss the compressive strength.

4.4.1 Mixes containing Perlite and Polypropylene (M17, M23-M25)

The Modulus of rupture and load-deflection relationship for each mix in this group is plotted in Figures 4.8 and 4.9.

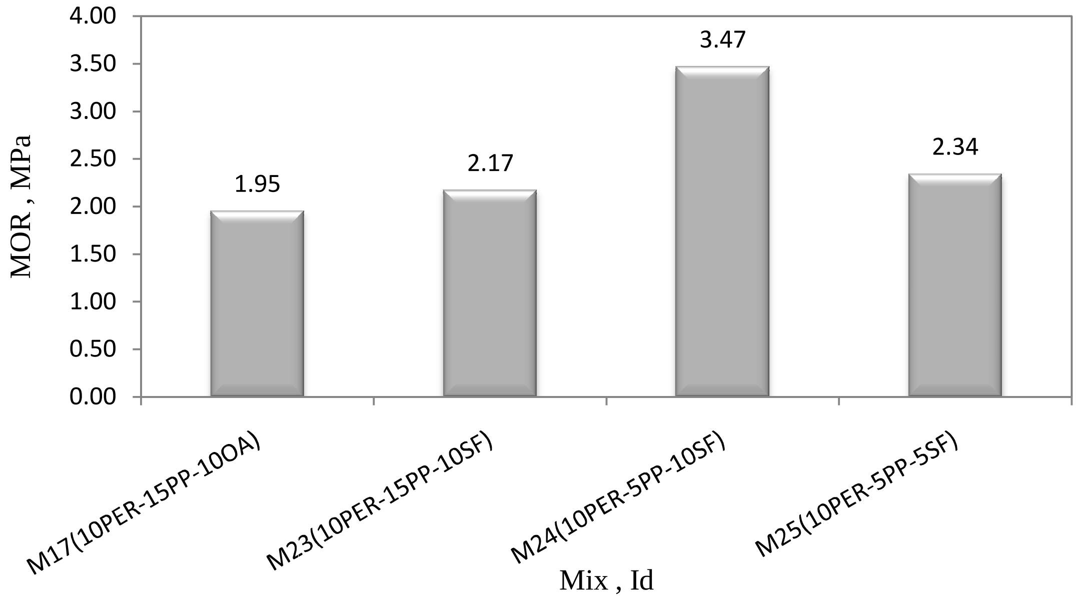


Figure 4.8: Average MOR for mixes with perlite and polypropylene.

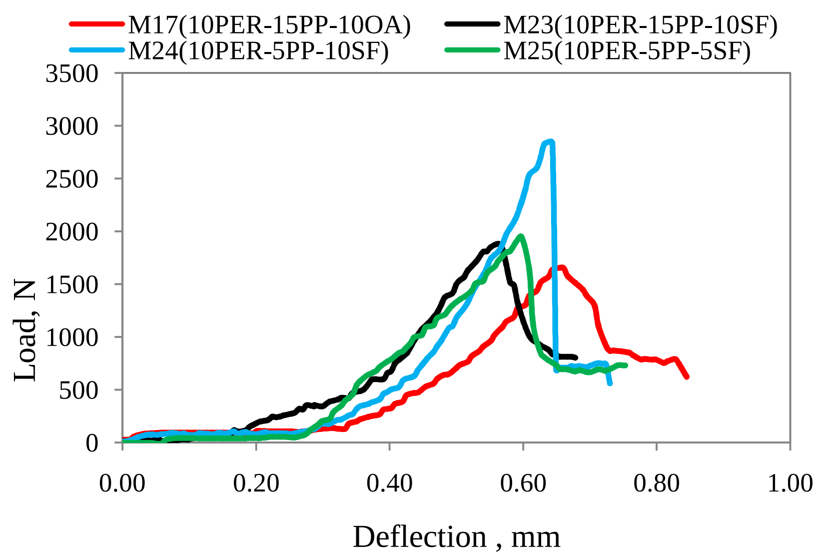


Figure 4.9: Load-Deflection relationship for mixes with perlite and polypropylene.

The highest MOR of this group of specimens was 3.47 MPa measured in mix (M24) having lowest percentage of polypropylene 5% and 10% perlite with maximum percentage of silica fume (10%). The lowest MOR was 1.95 MPa recorded in Mix (M17) with 15% polypropylene, 10% perlite, and 10%oil ash.

In mix M24 and M25, with the same percentage of perlite and Polypropylene, the change of silica fume percentage from 10% to 5% made a considerable reduction in the MOR which was 3.47 and 2.34 MPa, respectively.

It was observed from the load-deflection curves for the mixes in this group that the deflection was continued to increase without a parallel increase in load after failure, which means that the mixes of this group are more ductile due to the presence of Polypropylene.

4.4.2 Mixes containing Perlite and Scoria (M21, M27, M29-M32)

The MOR and load-deflection curves for the mixes in this group are plotted in Figures 4.10 and 4.11, respectively.

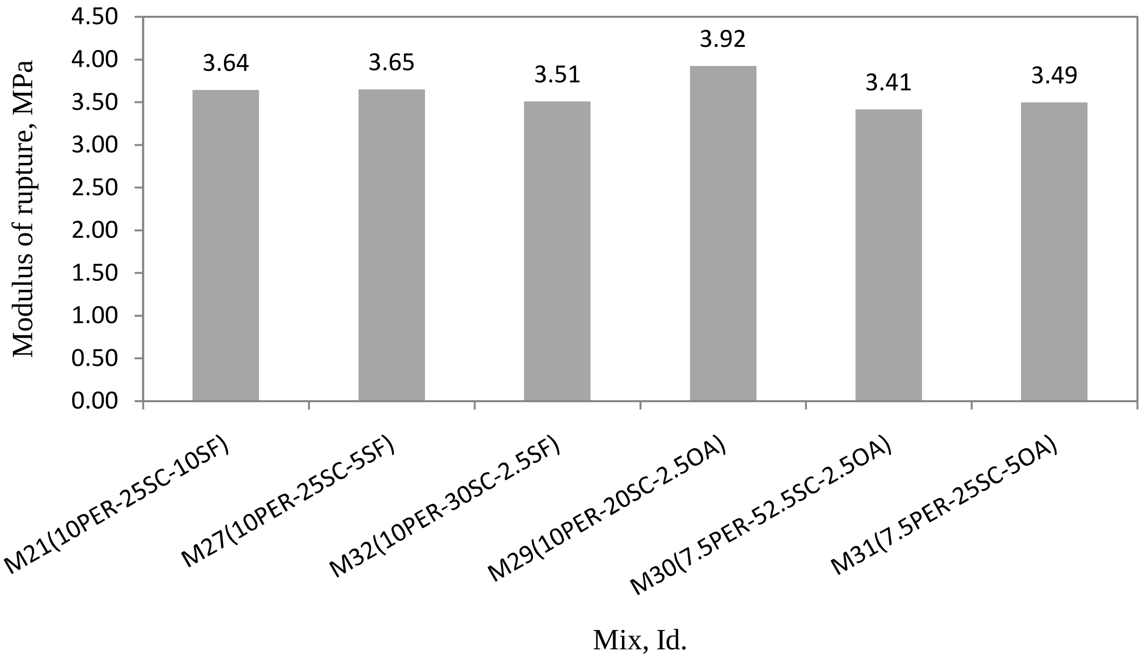


Figure 4.10: MOR for mixes with perlite and scoria.

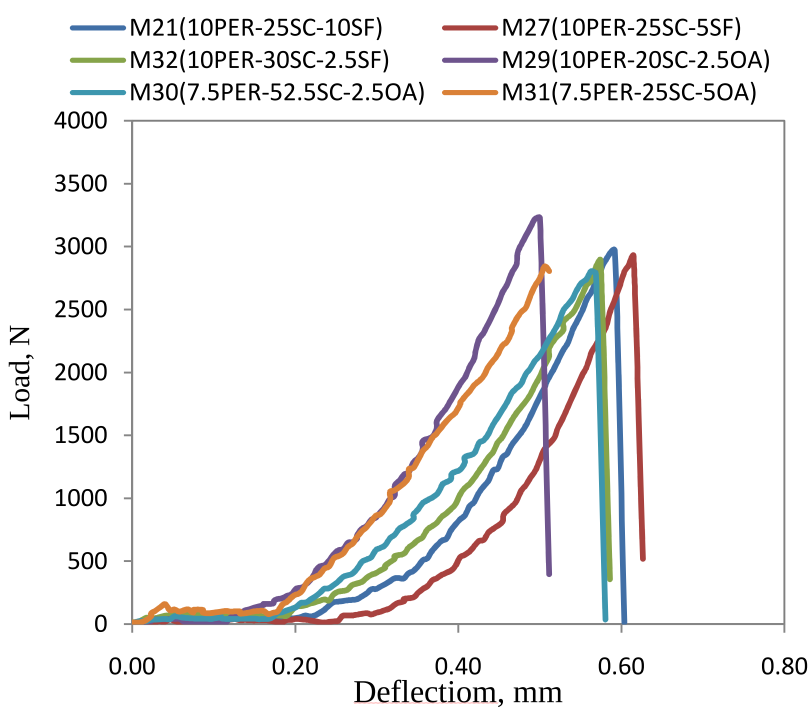


Figure 4.11: Load-Deflection relationship formixeswith perlite and scoria.

The highest MOR for this group was 3.92 MPa measured in mix (M29) having a 25% scoria, 10% perlite, and 2.5% oil ash. The lowest MOR was 3.41 MPa recorded in mix (M30) with 52.5% scoria, 7.5% perlite, and 2.5% oil ash.

The MOR of all mixes of perlite, scoria combination was more than 3.41 MPa(M21,M27,M29,M30,M31,and M32);The MOR was in the very close range of (3.41-3.92 MPa).

The MOR of two mixes with low percentage of perlite(7.5%) was 3.41 and 3.49 MPa.

It was observed from the load-deflection curves for these mixes that there was no more deflection after failure, indicating that these mixes are rigid due to the absence of polypropylene.

4.4.3 Mix containing Perlite without Scoria and polypropylene (M28)

As shown in Figure 4.7, mix (M28) had a MOR of (3.08 MPa) which was less than all mixes with scoria, and higher than mixes with high percentage of polypropylene.

It may be observed from the load-deflection curves for the mix contains perlite, as shown in Figure 4.12, that the specimen didn’t deflect after failure, which means that the mix of this group had very rigid pattern of failure due to the absence of Polypropylene.

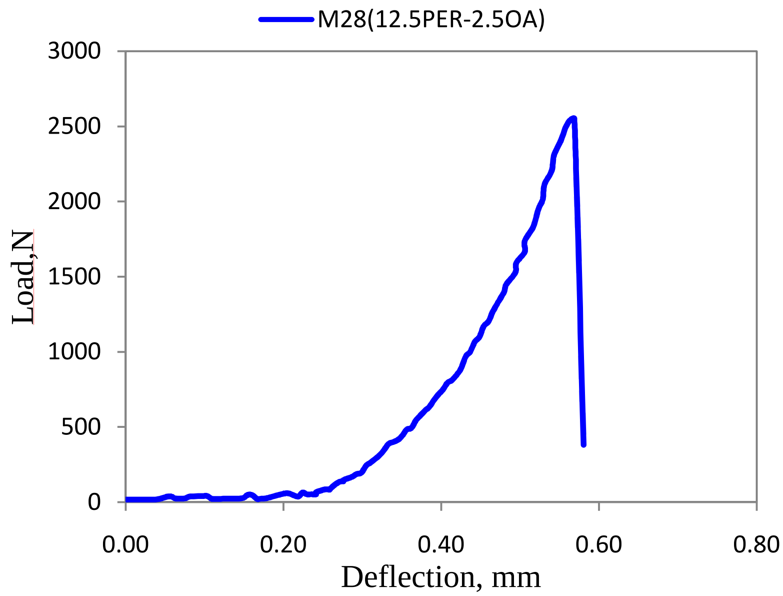


Figure 4.12: Load-Deflection curve for a mix containing Perlite.

4.4.4 Relationship between compressive and flexural strength

From the experimental data of compressive and flexural strength the relationships between the compressive (f_{cu}) and flexural (f_r) strength were obtained and compared to the relationship for normal weight concrete in foot-pound [58], and metric unit[59] as shown in Table 4.5.

Table 4.5: Correlation between compressive and flexural strength.

Unit	NWC	SLWC (PER-SC)	SLWC (PER-PP)
psi	$f_r=8.3\ f_{cu}^{1/2}$	$f_r=7.7\ f_{cu}^{1/2}$	$f_r=5.4\ f_{cu}^{1/2}$
MPa	$f_r=0.393\ f_{cu}^{2/3}$	$f_r=0.365\ f_{cu}^{2/3}$	$f_r=0.267\ f_{cu}^{2/3}$

The data in Table 4.5 indicate that Perlite-Scoria group has a close relationship to normal weight concrete.

4.5 Water Absorption

The 28-day average water absorption of the moist cured SLWC specimens is presented in Table 4.6, and depicted in Figure 4.13.

Table 4.6: Average 28-day water absorption in the SLWC mixes.

Mix #	Description of mix	Mix ID	Water absorption %
M17	10% Perlite, 15% polypropylene, and 10% Oil Ash of total aggregates.	M17 (10PER-15PP-10OA)	12.6
M21	10% Perlite, 25% Scoria, and 10% Silica Fume of total aggregates	M21 (10PER-25SC-10SF)	6.9
M23	10% Perlite, 15% Polypropylene, and 10% Silica Fume of total aggregates.	M23 (10PER-15PP-10SF)	9.2
M24	10% Perlite, 5% Polypropylene, and 10% Silica Fume of total aggregates.	M24 (10PER-5PP-10SF)	10.0
M25	10% Perlite, 5% polypropylene, and 5% Silica Fume of total aggregates.	M25 (10PER-5PP-5SF)	8.9
M27	10% Perlite, 25% Scoria, and 5% Silica Fume of total aggregates.	M27 (10PER-25SC-5SF)	8.8
M28	12.5% Perlite, and 2.5% Oil Ash of total aggregates.	M28 (12.5PER-2.5OA)	8.3
M29	10% perlite, 20% Scoria, and 2.5% Oil Ash of total aggregates.	M29(10PER-20SC-2.5OA)	6.5
M30	7.5% Perlite, 52.5% Scoria, and 2.5% Oil Ash of total aggregates.	M30 (7.5PER-52.5SC-2.5OA)	9.0
M31	7.5% Perlite, 25%Scoria, and 5% Oil Ash of total aggregates.	M31 (7.5PER-25SC-5OA)	9.4
M32	10% Perlite, 30%Scoria, and 2.5% Silica Fume of total aggregates.	M32 (10PER-30SC-2.5SF)	7.8

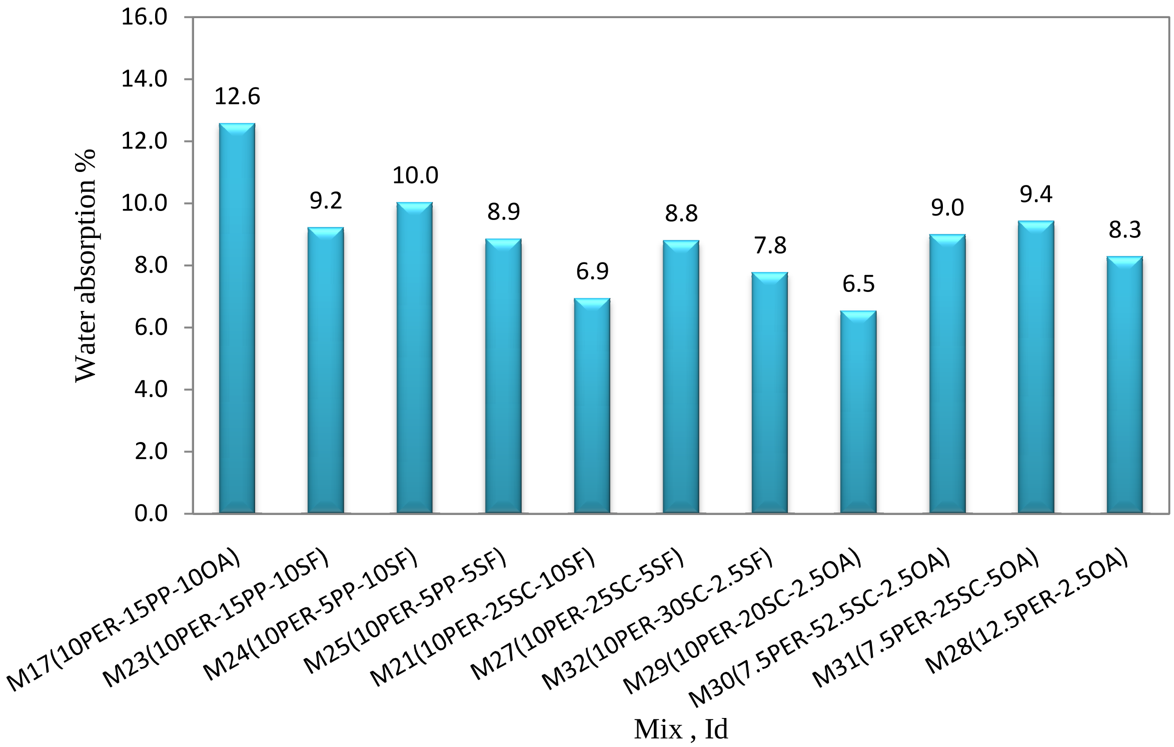


Figure 4.13: Average 28-day water absorption in the SLWC mixes.

The highest water absorption of 12.6% was measured in mix (M17) that contains highest percentage of polypropylene (15%) and oil ash (10%). The increased water absorption may attribute to the high quantity of OA. The lowest water absorption of 6.5 % was recorded in mix (M29) which has the lowest percentage of scoria (20%) and oil ash (2.5%).

The water absorption of the SLWC mixes will be discussed in the same groups that were used earlier.

4.5.1 Mixes containing Perlite and Polypropylene (M17, M23-M25)

The 28-day water absorption for mixes in this group is plotted in Figure 4.14.

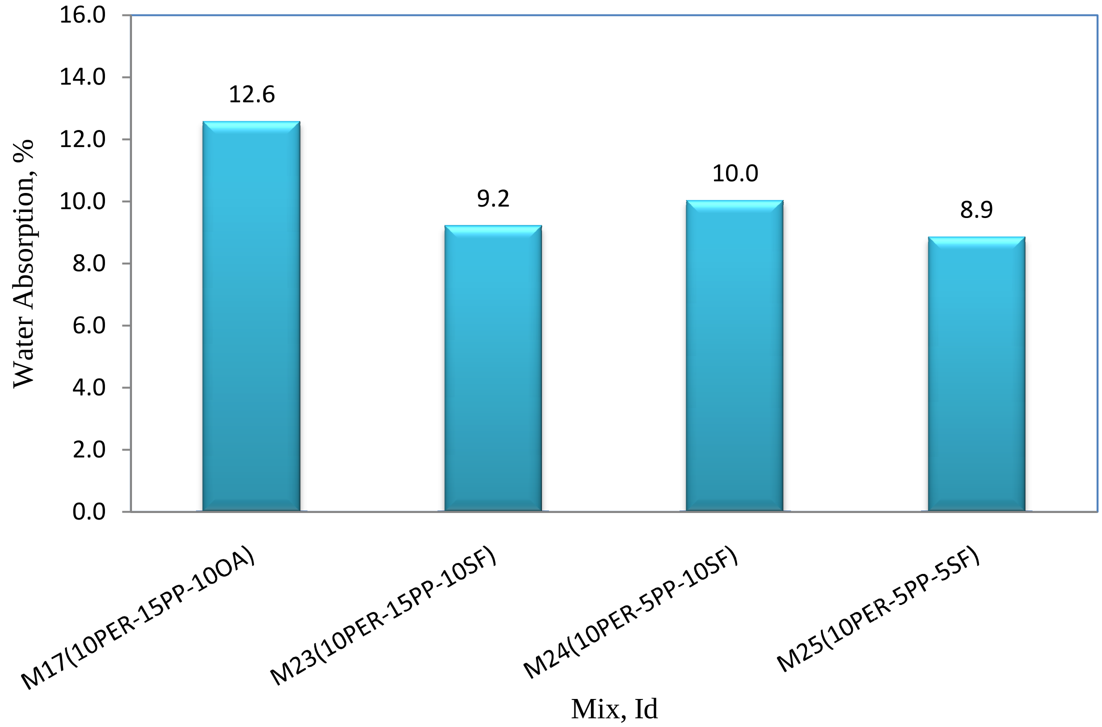


Figure 4.14: Average 28-day water absorption for mixes with perlite and polypropylene.

The lowest water absorption in this group was 8.9% measured in mix (M25) with the lowest percentage of polypropylene (5%), silica fume (5%), and perlite (10%).The highest water absorption was 12.6 % recorded in mix (M17) with the highest percentage of polypropylene (15%), oil ash (10%), and (10%) perlite.

For mixes M24 and M25, with the same percentage of perlite and polypropylene, the change of silica fume content from 10% to 5%decreased the water absorption from 10% to 8.9%.

For mixes M17 and M23, for the same percentage of perlite and polypropylene, the quantity of oil ash has clear effect on the water absorption over silica fume. The water absorption of specimen with oil ash was 12.6% compared to 9.2% in the specimen with silica fume (M23). This may be attributed to a decrease in the workability of oil ash specimen that led to the formation of voids.

4.5.2 Mixes containing Perlite and Scoria (M21, M27, M29-M32)

The 28-day water absorption in the specimens in this group is plotted in Figure 4.15.

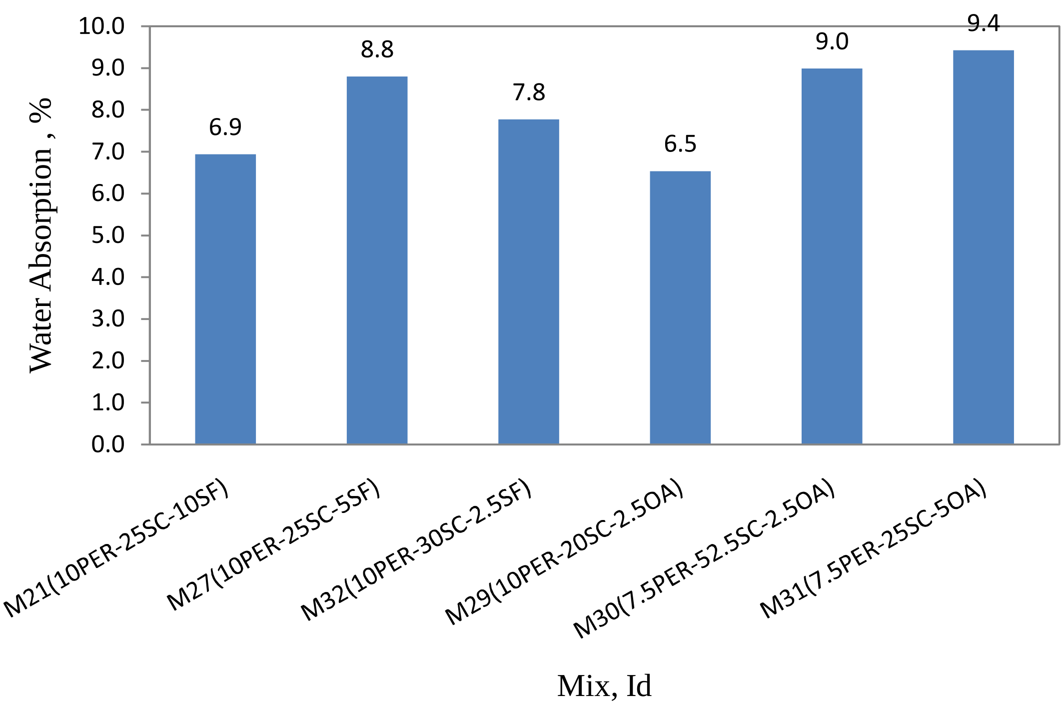


Figure 4.15: Average 28-day water absorption in the mixes with perlite and scoria.

The maximum water absorption in this group of specimens was 9.4% measured in mix (M31) having 25% of scoria, 10% perlite, and 5% oil ash. The lowest water absorption of 6.5% was recorded in mix (M29) with lowest percentage of scoria (20%), minimum oil ash (2.5%), and 10 % perlite.

The water absorption in mix (M30) was 9% as it contains high percentage of scoria (52.5%) in spite of the lowest percentage of perlite (7.5%).

4.5.3 Mix containing Perlite without Scoria and polypropylene (M28)

The water absorption (8.3%) of this mix (M28), Figure 4.10, is less than that of all other mixes with perlite and polypropylene combination.

The results discussed earlier indicate that scoria, oil ash, and polypropylene are the most effective light weight materials in the water absorption. Although the water absorption of SLWC is a little bit more than NWC but these results give only an estimation of the total reachable pore volume of the concrete, but they are not accurate indicator of concrete permeability [60].

4.6 Chloride Permeability

The standard classification of the Chloride Ion Penetrability based on Charge Passed according to ASTM C1202 [21] is given in Table 4.7.

Table 4.7: Chloride Ion Penetrability Based on Charge Passed [21].

Charge Passed (coulombs)	Chloride Ion Penetrability
>4,000	High
2,000–4,000	Moderate
1,000–2,000	Low
100–1,000	Very Low
<100	Negligible

The 28-day average chloride permeability of the SLWC specimens is presented in Table 4.8, and depicted in Figure 4.16.

Table 4.8: Average 28-day Chloride Permeability of SLWC mixes.

Mix #	Description of mix	Mix ID	Charge Passed (coulombs)	Chloride Ion Penetrability
M17	10% Perlite, 15% polypropylene, and 10% Oil Ash of total aggregates.	M17(10PER-15PP-10OA)	7315	High
M21	10% Perlite, 25% Scoria, and 10% Silica Fume of total aggregates	M21(10PER-25SC-10SF)	738	Very Low
M23	10% Perlite, 15% Polypropylene, and 10% Silica Fume of total aggregates.	M23(10PER-15PP-10SF)	457	Very Low
M24	10% Perlite, 5% Polypropylene, and 10% Silica Fume of total aggregates.	M24(10PER-5PP-10SF)	271	Very Low
M25	10% Perlite, 5% polypropylene, and 5% Silica Fume of total aggregates.	M25(10PER-5PP-5SF)	886	Very Low
M27	10% Perlite, 25% Scoria, and 5% Silica Fume of total aggregates.	M27(10PER-25SC-5SF)	941	Very Low
M28	12.5% Perlite, and 2.5% Oil Ash of total aggregates.	M28(12.5PER-2.5OA)	1863	Low
M29	10% perlite, 20% Scoria, and 2.5% Oil Ash of total aggregates.	M29(10PER-20SC-2.5OA)	2369	Moderate
M30	7.5% Perlite, 52.5% Scoria, and 2.5% Oil Ash of total aggregates.	M30(7.5PER-52.5SC-2.5OA)	2875	Moderate
M31	7.5% Perlite, 25%Scoria, and 5% Oil Ash of total aggregates.	M31(7.5PER-25SC-5OA)	2719	Moderate
M32	10% Perlite, 30%Scoria, and 2.5% Silica Fume of total aggregates.	M32(10PER-30SC-2.5SF)	1405	Low

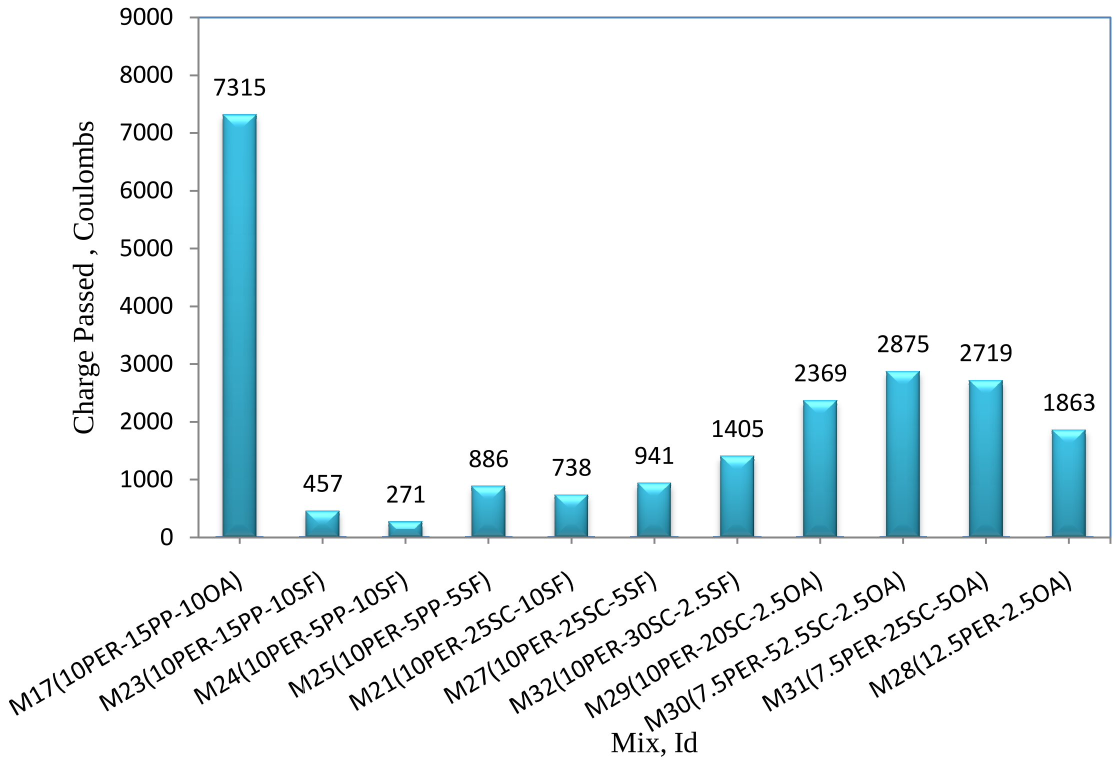


Figure 4.16: Average 28-day Chloride Permeability in SLWC mixes.

The highest value of chloride permeability, expressed in charge passed, was 7315 coulombs recorded in mix (M17) that contains 10% oil ash, and 15% polypropylene. The lowest value of chloride permeability was 271 coulombs recorded in mix (M24) which has the highest percentage of silica fume (10%) and the lowest percentage of PP (5%).

All the mixes with silica fume showed very low to low chloride permeability in contrast to mixes with oil ash in which the chloride permeability was moderate to high.

The chloride permeability of the SLWC mixes will be discussed in three groups as was done earlier.

4.6.1 Mixes containing Perlite and Polypropylene (M17, M23-M25)

The 28-day chloride permeability for mixes in this group is plotted in Figure 4.17.

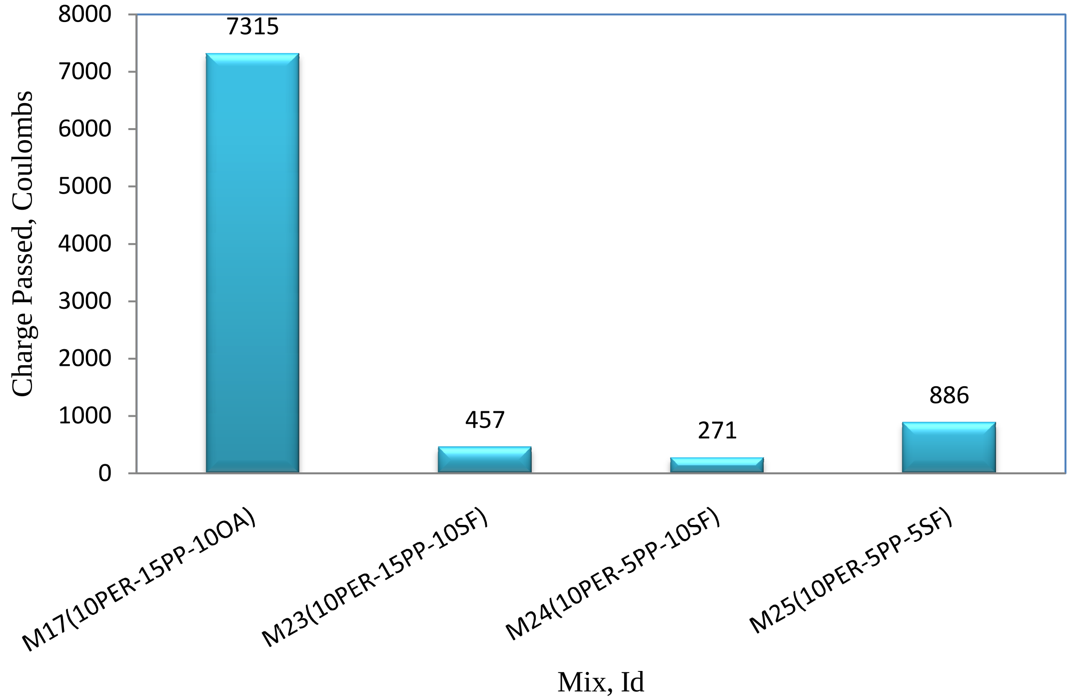


Figure 4.17: Average 28-day chloride permeability of mixes with perlite and polypropylene.

The lowest chloride permeability in this group was 271 coulombs measured in mix (M24) having the highest percentage of silica fume (10%) that make the microstructure denser, the lowest percentage of polypropylene (5%), and perlite of (10%). The highest chloride permeability was 7315 coulombs recorded in mix (M17) with the highest percentage of polypropylene (15%), oil ash (10%), and (10%) perlite.

For mixes M23 and M24, for same percentage of perlite and silica fume, the reduction in polypropylene content from 15% in M23 to 5% in M24 slightly decreased the chloride permeability from 457 to 271 Coulombs.

For mixes M24 and M25, for the same percentage of perlite and Polypropylene, the reduction in the quantity of silica fume percentage from 10% to 5% slightly increased the chloride permeability from 271 to 886 coulombs.

For mixes M17 and M23, with the same percentage of perlite and polypropylene, the oil ash has clear affect on the chloride permeability over the silica fume as its specimen (M17) has7315 coulombs compared to 457 coulombs for the silica fume specimen (M23). Therefore the oil ash has the greatest effect on chloride permeability for this group.

4.6.2 Mixes containing Perlite and Scoria (M21, M27, M29-M32)

The 28-day chloride permeability of mixes in this group is plotted in Figure 4.18.

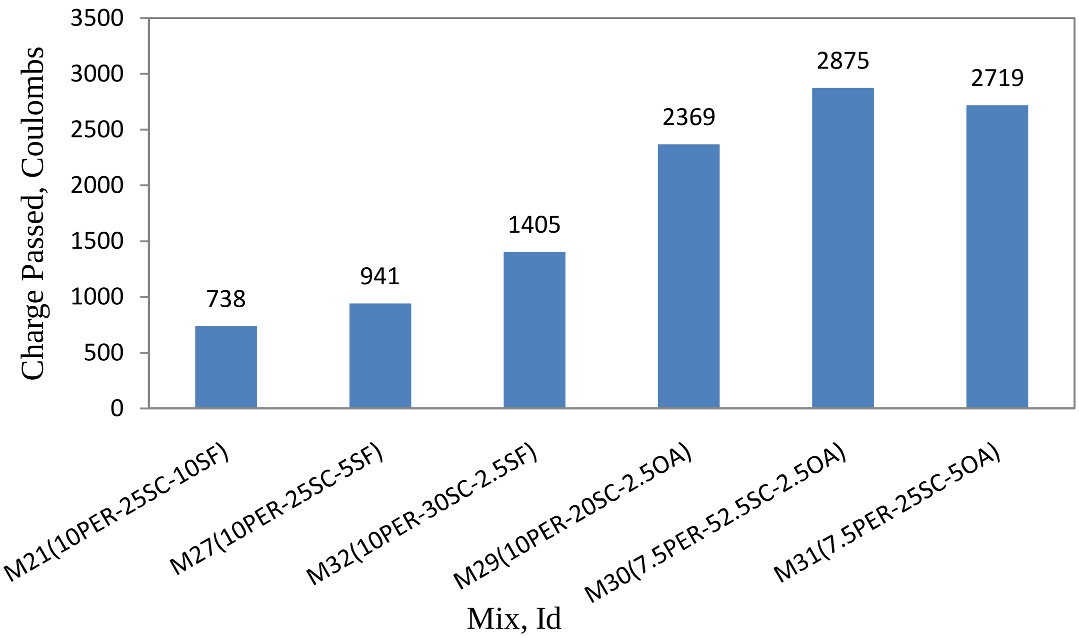


Figure 4.18: Average 28-days chloride permeability of mixes with perlite and scoria.

The maximum chloride permeability in this group was 2875coulombs measured in mix (M30) having the highest percentage of scoria (52.5%), 7.5% perlite, and 2.5% oil ash. The lowest chloride permeability of 738 was recorded in mix (M21) with 25% scoria, 10% perlite, and 10% silica fume .Therefore, scoria has the greatest effect on the chloride permeability in this group.

Mix (M31) has high chloride permeability (2719 coulombs) as it contains a little bit high percentage of oil ash (5%).

4.6.3 Mix containing Perlite without Scoria and polypropylene (M28)

The chloride permeability of this mix (M28) was 1863 coulombs; see Figure 4.16, which is still in the low range in spite of the highest percentage of perlite (12.5%) indicating that perlite has a very insignificant effect on the chloride permeability.

The chloride permeability results, discussed earlier indicate that oil ash and scoria are the most effective light weight materials in increasing the chloride permeability.

4.7 Thermal conductivity

Thermal conductivity of the SLWC slab specimens are presented in Table 4.9, and depicted in Figure 4.19.

Table 4.9 : Thermal conductivity ofdeveloped SLWC mixes.

Mix #	Description of mix	Mix ID	Thermal Conductivity (W/m.K)
M17	10% Perlite, 15% polypropylene, and 10% Oil Ash of total aggregates.	M17(10PER-15PP-10OA)	0.460
M21	10% Perlite, 25% Scoria, and 10% Silica Fume of total aggregates.	M21(10PER-25SC-10SF)	0.482
M23	10% Perlite, 15% Polypropylene, and 10% Silica Fume of total aggregates.	M23(10PER-15PP-10SF)	0.413
M24	10% Perlite, 5% Polypropylene, and 10% Silica Fume of total aggregates.	M24(10PER-5PP-10SF)	0.657
M25	10% Perlite, 5% polypropylene, and 5% Silica Fume of total aggregates.	M25(10PER-5PP-5SF)	0.431
M27	10% Perlite, 25% Scoria, and 5% Silica Fume of total aggregates.	M27(10PER-25SC-5SF)	0.362
M28	12.5% Perlite, and 2.5% Oil Ash of total aggregates.	M28(12.5PER-2.5OA)	0.393
M29	10% perlite, 20% Scoria, and 2.5% Oil Ash of total aggregates.	M29(10PER-20SC-2.5OA)	0.368
M30	7.5% Perlite, 52.5% Scoria, and 2.5% Oil Ash of total aggregates.	M30(7.5PER-52.5SC-2.5OA)	0.483
M31	7.5% Perlite, 25%Scoria, and 5% Oil Ash of total aggregates.	M31(7.5PER-25SC-5OA)	0.369
M32	10% Perlite, 30%Scoria, and 2.5% Silica Fume of total aggregates.	M32(10PER-30SC-2.5SF)	0.387

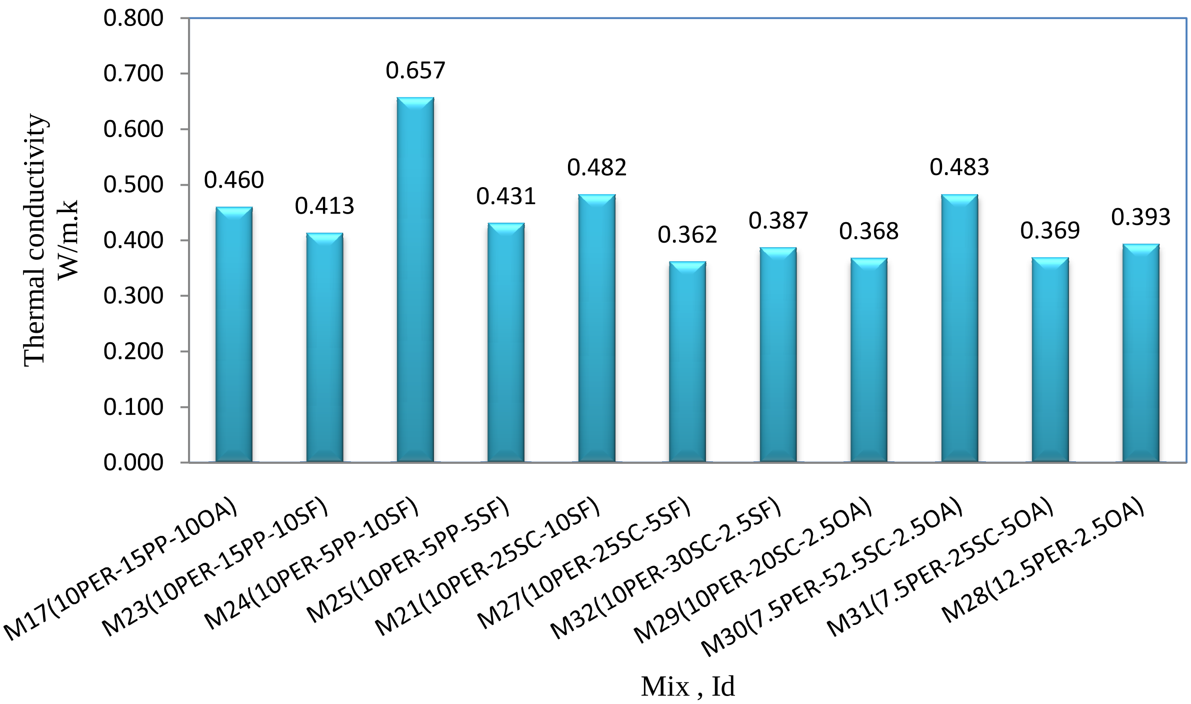


Figure 4.19: Thermal conductivity of developed SLWC mixes.

The highest value of thermal conductivity, k-value, of 0.657 W/m.K was recorded in mix (M24) that contains lowest percentage of polypropylene (5%), highest percentage of silica fume (10%), and 10% perlite. The lowest value of thermal conductivity was 0.362 W/m.K recorded in mix (M27) which has 25% scoria, 10% perlite, and 5 % silica fume.

All SLWC mixes shows low thermal conductivity values compared to NWC that have thermal conductivity in the range of 1.185 to 1.448 W/m.K[33]. The thermal conductivity of the SLWC mixes will be discussed in the three groups as was done earlier.

4.7.1 Mixes containing Perlite and Polypropylene (M17, M23-M25)

The thermal conductivity for mixes in this group is plotted in Figure 4.20.

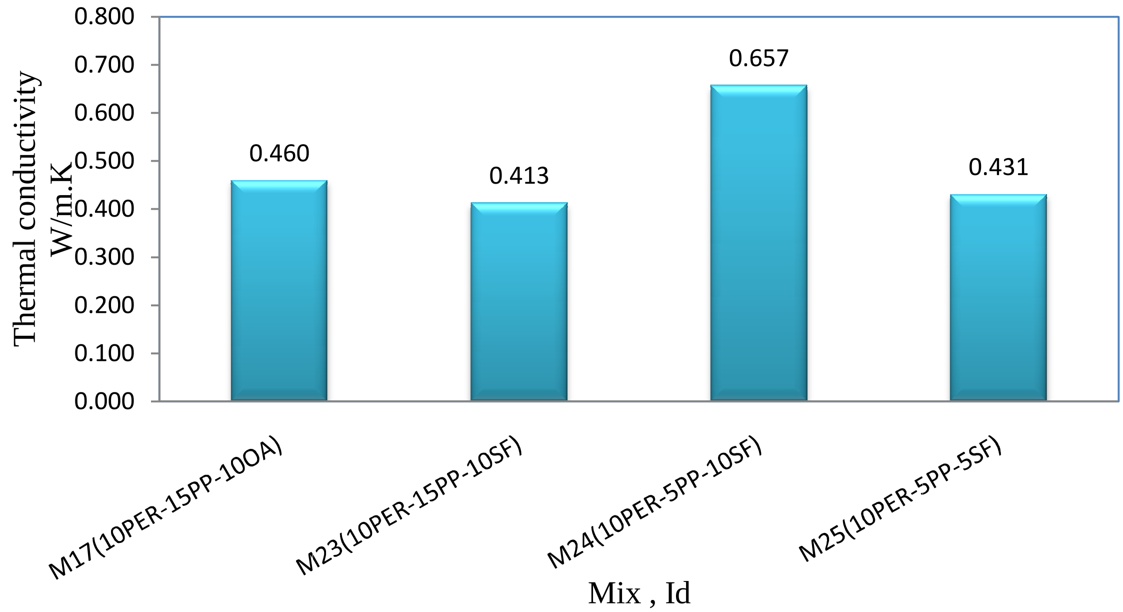


Figure 4.20: Thermal conductivity of mixes with perlite and polypropylene.

The lowest thermal conductivity of this group was 0.413 W/m.K measured in mix (M23) with the highest percentage of polypropylene (15%), perlite (10%), and the highest percentage of silica fume (10%).The highest thermal conductivity of 0.657 W/m.K was recorded in mix (M24) with the lowest percentage of polypropylene used (5%), perlite (10%), and silica fume (10%).

For mixes M23 and M24, with the same percentage of perlite and silica fume, the reduction in polypropylene quantity from 15% in M23 to 5% in M24 increases the thermal conductivity from 0.413 to 0.657 W/m.K.

For mixes M24 and M25, with the same percentage of perlite and polypropylene, the reduction in the quantity of silica fume from 10% to 5% decreases the thermal conductivity from 0.657 to 0.431 W/m.K.

For mixes M17 and M23, with the same quantity of perlite and Polypropylene, the mix withoil ash has a thermal conductivity of 0.460 W/m.K compared to 0.413 W/m.K for the mix with silica fume (M23).

Therefore, the incorporation of polypropylene and perlite has the greatest effect on thermal conductivity in this group of specimens.

4.7.2 Mixes containing Perlite and Scoria (M21, M27, M29-M32)

Thermal conductivity for mixes in this group is plotted in Figure 4.21.

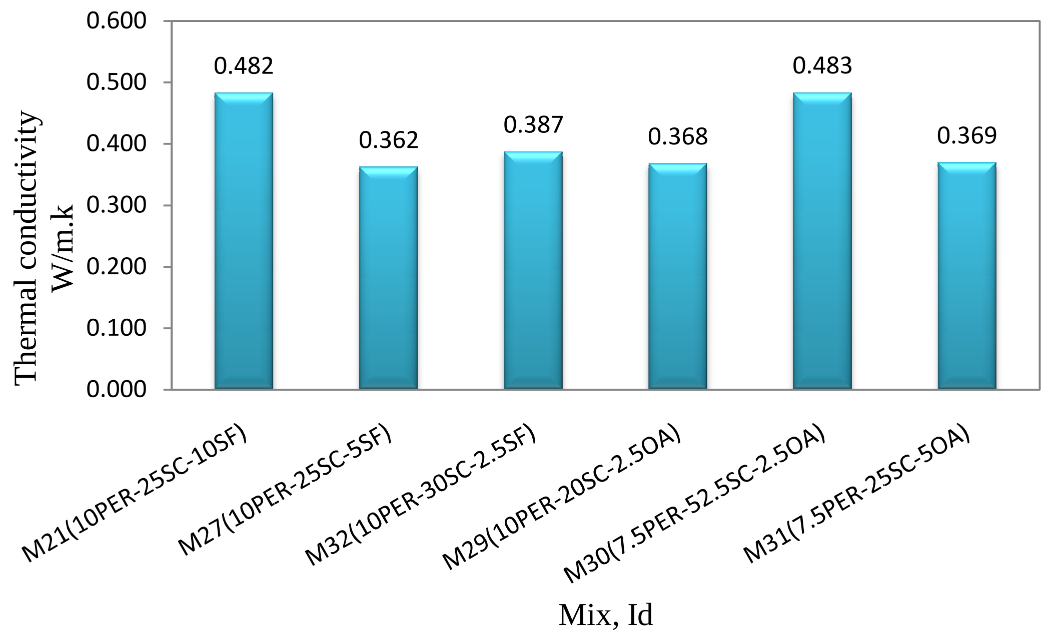


Figure 4.21: Thermal conductivity of mixes with perlite and scoria.

The highest thermal conductivity in this group was 0.483 W/m.K measured in mix (M30) having the lowest percentage of perlite (7.5%), in spite of the highest percentage of Scoria (52.5%). Therefore perlite has a great effect on the thermal conductivity. The lowest thermal conductivity of 0.362W/m.K was recorded in mix (M27) with 25% scoria, 10% perlite, and 5% silica fume.

In mixes M21 and M27, with the same percentage of perlite and scoria, the reduction of silica fume content from (10% to 5%), also, decreased the thermal conductivity from 0.482 to 0.362 W/m.K.

4.7.3 Mix containing Perlite without Scoria and polypropylene (M28)

The thermal conductivity of this mix was 0.393 W/m.K, Figure 4.19, which is in the low range, because of highest percentage of perlite (12.5%), but not the lowest because of the absence of scoria or polypropylene.

4.8 Drying shrinkage

The average drying shrinkage of the developed SLWC specimens measured over a period of 92 days is presented in Table 4.10.

Table 4.10: Drying shrinkage of the developed SLWC mixes.

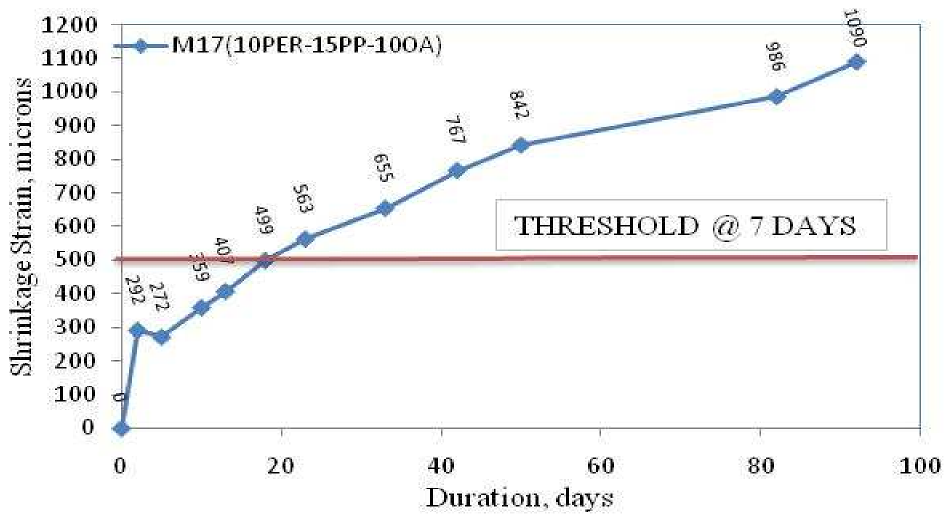
Duration, days	Drying shrinkage, microns										
	M17	M21	M23	M24	M25	M27	M28	M29	M30	M31	M32
0	0	0	0	0	0	0	0	0	0	0	0
2	-292	-207	-551	-128	-451	-112	-16	211	-52	-48	-258
5	-272	-216	-659	-639	-527	-199	-108	275	-96	-64	-309
10	-359	-463	-755	-631	-638	-287	-331	-16	-236	-224	-545
13	-407	-343	-878	-695	-638	-351	-514	-211	-363	-328	-569
18	-499	-447	-1014	-947	-718	-431	-665	-275	-539	-352	-756
23	-563	-614	-1134	-1047	-946	-534	-777	-355	-575	-440	-867
33	-655	-654	-1154	-1079	-993	-694	-797	-532	-679	-484	-955
42	-767	-702	-1282	-1218	-1073	-694	-908	-566	-691	-520	-1035
50	-842	-814	-1405	-1294	-1137	-821	-1028	-614	-711	-576	-1123
82	-986	-902	-1665	-1418	-1305	-1053	-1092	-725	-887	-639	-1211
92	-1090	-1041	-1784	-1514	-1396	-1092	-1175	-785	-978	-683	-1235

The drying shrinkage of the developed SLWC mixes will be discussed in three same groups as was done earlier.

4.8.1 Mixes containing Perlite and Polypropylene (M17, M23-M25)

The average drying shrinkage strain over a period of 92 days, for the mixes in this group, is plotted in Figure 4.22.

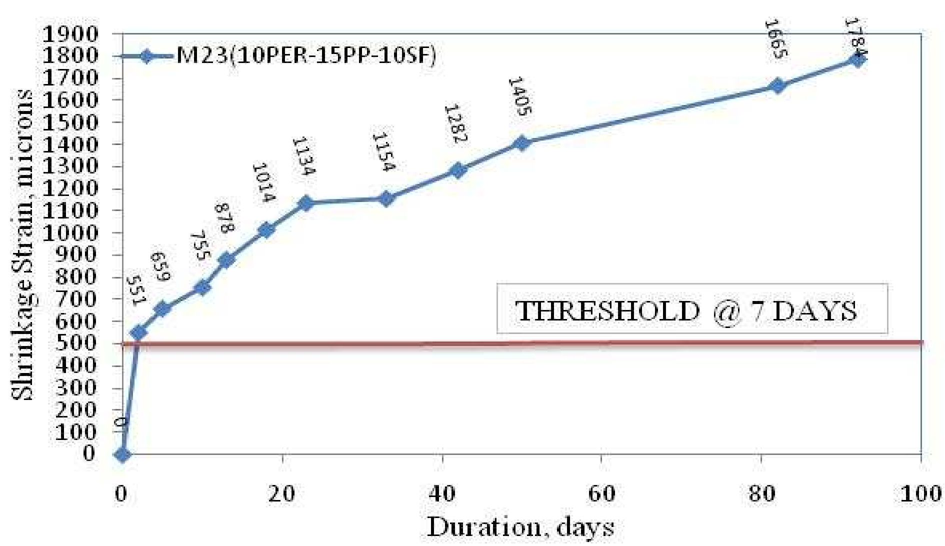
4.8.1.1 Mix M17 (10PER-15PP-10OA)



(a): Drying shrinkage strain inMix M17.

The average drying shrinkage strain is more than the threshold value of 500 microns after 18 days. The average drying shrinkage strain after 92 days was 1090 microns. The drying shrinkage strain increases linearly in the first 50 days.

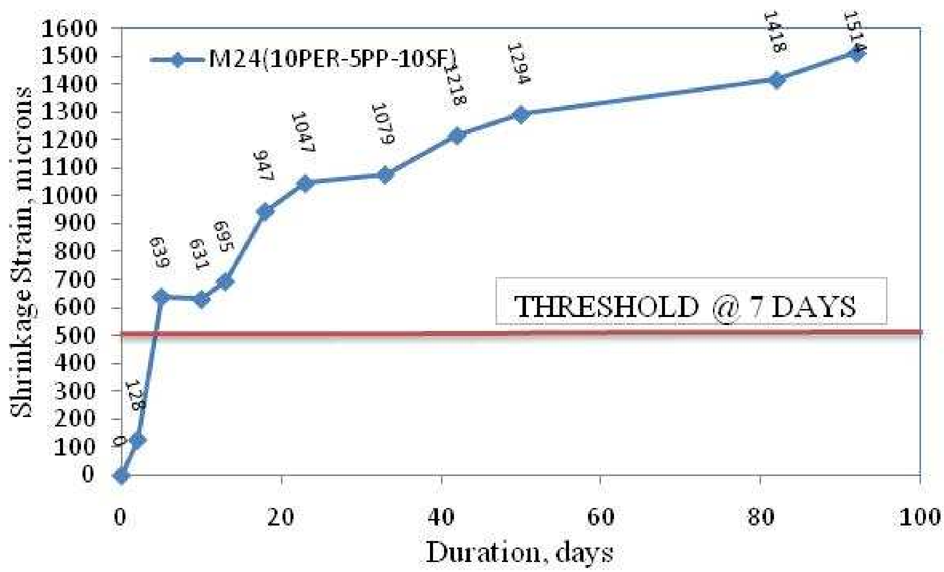
4.8.1.2 Mix M23 (10PER-15PP-10SF)



(b): Drying shrinkage strain for Mix M23.

The average drying shrinkage strain reached the threshold value of 500 microns after only 2 days. The average drying shrinkage strain after 92 days was 1784 microns.

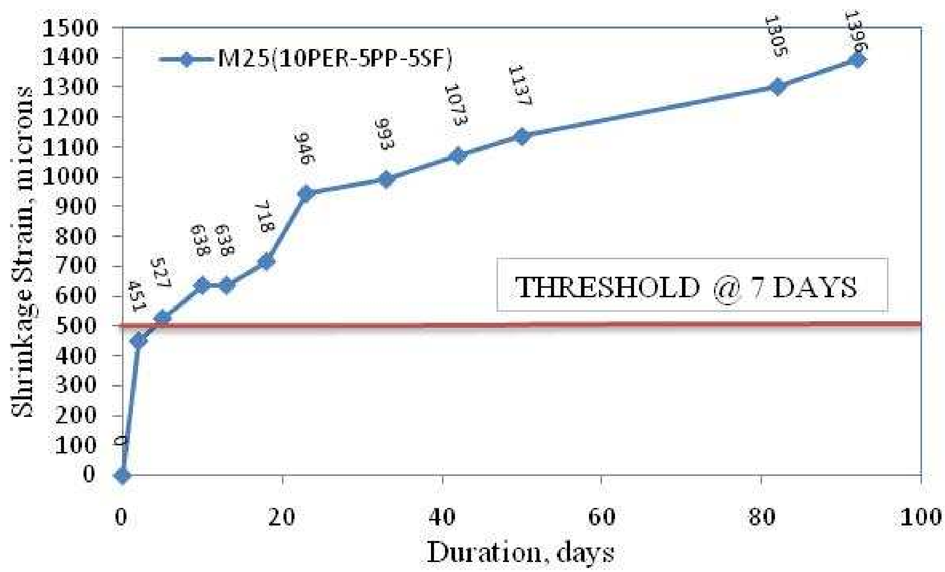
4.8.1.3 Mix M24 (10PER-5PP-10SF)



(c): Drying shrinkage strain in mix M24.

The average drying shrinkage strain reached the threshold value of 500 microns after only 4 days. The average drying shrinkage strain after 92 days was 1514 microns.

4.8.1.4 Mix M25 (10PER-5PP-5SF)



(d): Drying shrinkage strain in mix M25.

Figure 4.22: Drying shrinkage strain in SLWC mixes with perlite and polypropylene.

The average drying shrinkage strain reached the threshold value of 500 microns after only 4 days. The average drying shrinkage strain after 92 days was 1396 microns.

In the four mixes with perlite and polypropylene combination group, the highest drying shrinkage strain of 1784 microns was measured in mix (M23) having the highest percentage of polypropylene (15%), perlite of (10%), and the highest percentage of silica fume (10%).The lowest drying shrinkage strain of 1090 microns was recorded in mix (M17) having the highest percentage of oil ash (10%),perlite (10%), and polypropylene (15%). In this mix in spite of the highest percentage of polypropylene, the drying shrinkage strain is low because of the highest percentage of oil ash. All mixes in this group has reached the drying shrinkage strain threshold in less than a week, except mix (M17), that contains oil ash, the threshold is crossed after 18 days.

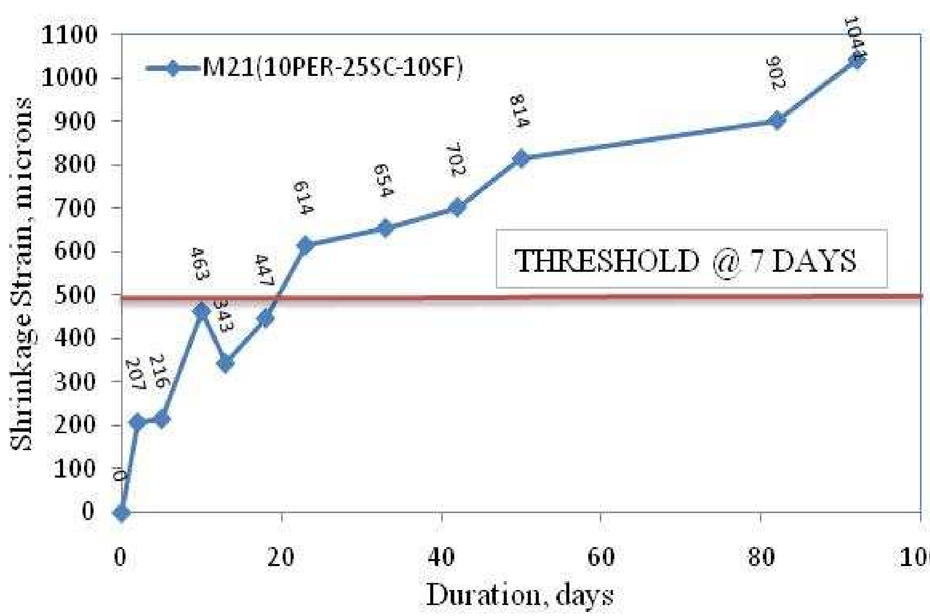
In mixes M23 and M24, with the same quantities of perlite and silica fume, the reduction in polypropylene content from 15% in (M23) to 5% in (M24) decreased the drying shrinkage strain from 1784 to 1514 microns in 92 days.

In mixes M17 and M23, for the same percentage of perlite and polypropylene, mix with oil ash has a very lower drying shrinkage strain than mix with silica fume. The drying shrinkage strain in the former mix was 1090 microns compared to 1784 microns in the silica fume specimen (M23).

4.8.2 Mixes containing Perlite and Scoria (M21, M27, M29-M32)

The drying shrinkage strain in the mixtures of this group is plotted in Figure 4.23.

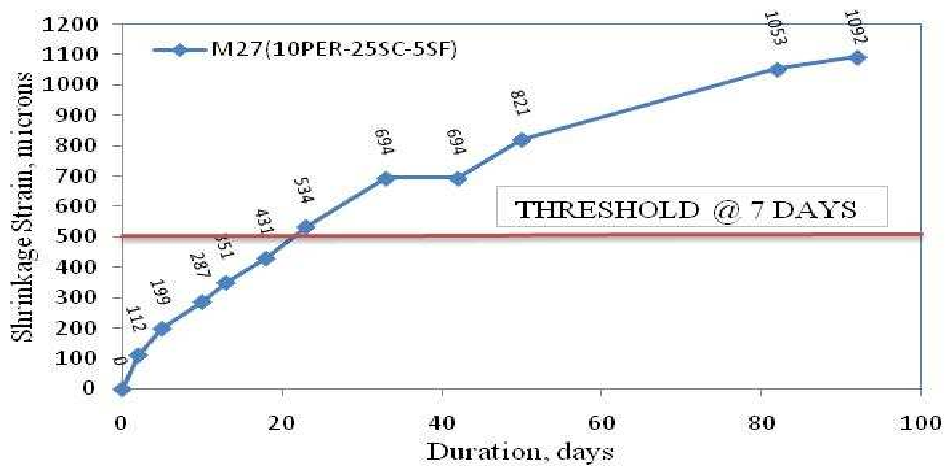
4.8.2.1 Mix M21 (10PER-25SC-10SF)



(a): Drying shrinkage strain in mix M21.

The average drying shrinkage strain in this mix reached the threshold value of 500 microns after 20 days. The drying shrinkage strain after 92 days was 1041 microns.

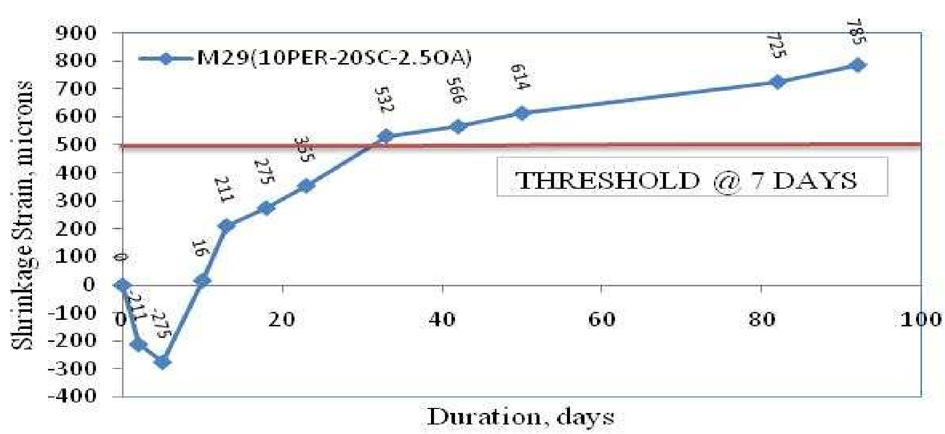
4.8.2.2 Mix M27 (10PER-25SC-5SF)



(b): Drying shrinkage strain for mix M27.

The average drying shrinkage strain crossed the threshold value of 500 microns after 21days. The drying shrinkage strain after 92 days was1092 microns.

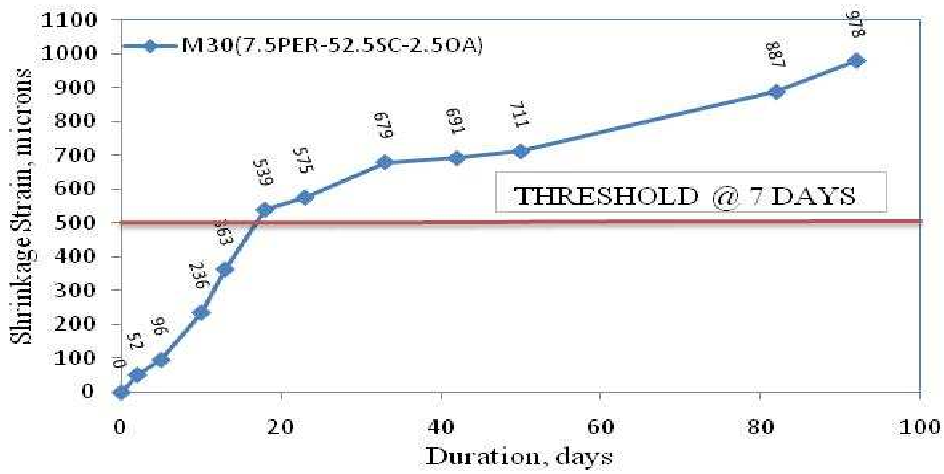
4.8.2.3 Mix M29 (10PER-20SC-2.5OA)



(c): Drying shrinkage strain in mix M29.

The average drying shrinkage strain crossed the threshold value of 500 microns after 32 days. The drying shrinkage strain after 92 days was 785 microns.

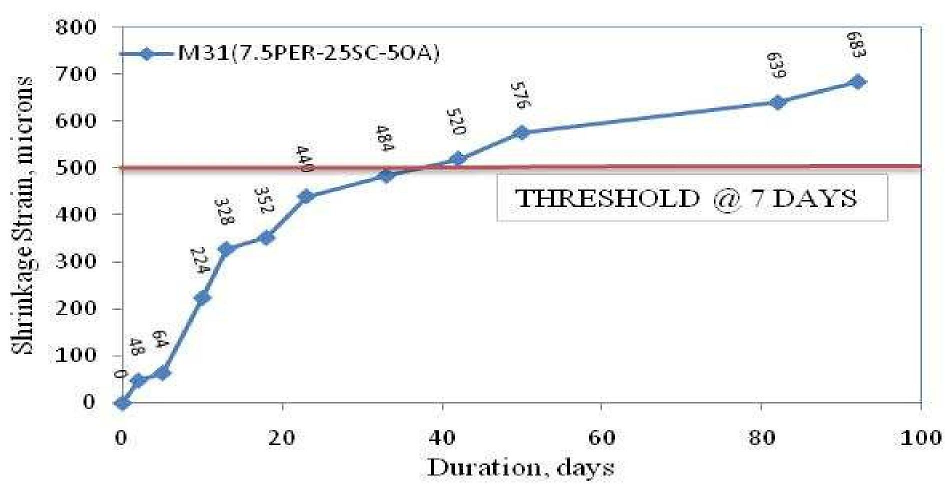
4.8.2.4 Mix M30 (7.5PER-52.5SC-2.5OA)



(d): Drying shrinkage strain in mix M30.

The average drying shrinkage strain reached the threshold value of 500 microns after 17 days. The drying shrinkage strain after 92 days was 978 microns.

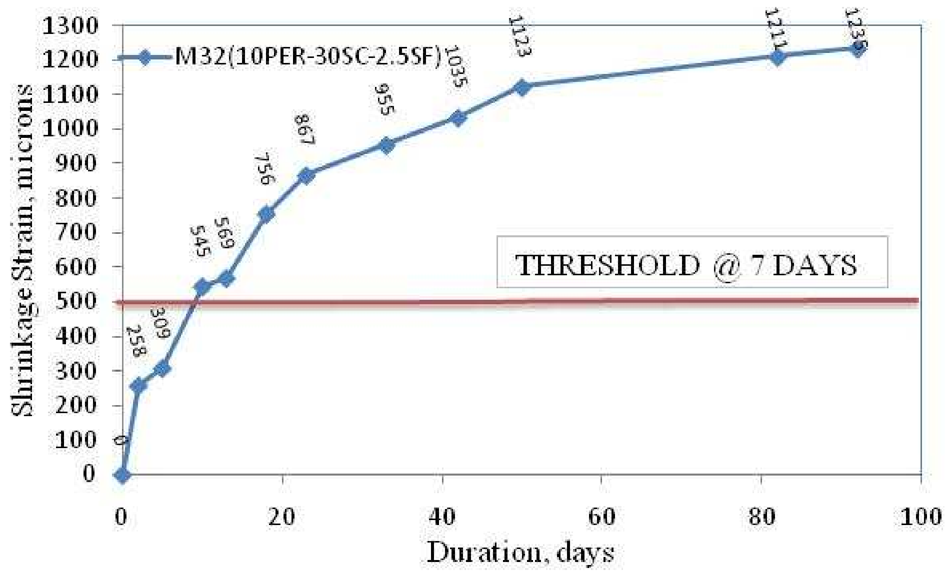
4.8.2.5 Mix M31 (7.5PER-25SC-5OA)



(e): Drying shrinkage strain for mix M31.

The average drying shrinkage strain crossed the threshold value of 500 microns after 36 days. The drying shrinkage strain after 92 days was 683 microns.

4.8.2.6 Mix M32 (10PER-30SC-2.5SF)



(f): Drying shrinkage strain in mix M32.

Figure 4.23: Drying shrinkage strain in SLWC mixes with perlite and scoria.

The average drying shrinkage strain crossed the threshold value of 500 microns after 9 days. The drying shrinkage strain after 92 days was 1235 microns.

In the six mixes with perlite and scoria combination group, the highest drying shrinkage strain was 1235 microns measured in mix (M32) having 30% scoria, 10% perlite, and 2.5% silica fume. The lowest drying shrinkage strain of 683 microns was recorded in mix (M31) with 25%scoria, 7.5% perlite, and 5% oil ash.

All mixes in this group crossed the drying shrinkage strain threshold after the first week. Mixes containing oil ash, mixes M29, M30, and M31, have lower drying shrinkage strain compared to mixes that contain silica fume M21, M27, and M32.

4.8.3 Mix containing Perlite without Scoria and polypropylene M28

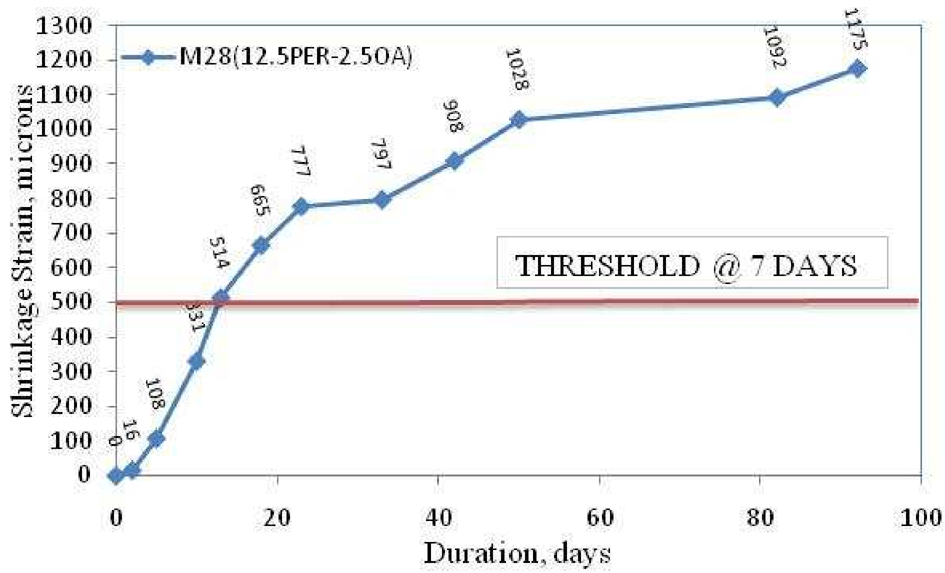


Figure 4.24: Drying shrinkage strain in mix M28.

The average drying shrinkage strain reached the threshold value of 500 microns after 12 days. The drying shrinkage strain after 92 days was 1175 microns, see Figure 4.21.

4.9 Corrosion potentials

According to ASTM C876 method to determine the corrosion activity of the reinforcing steel, the threshold value is - 270 mV SCE for the standard Calomel electrode [22] used for this monitoring process. The average Corrosion potential measured up to 90 days of exposure to 5% NaCl solution is presented in Table 4.11.

Table 4.11: Average corrosion potentials on steel in the developed SLWC mixes.

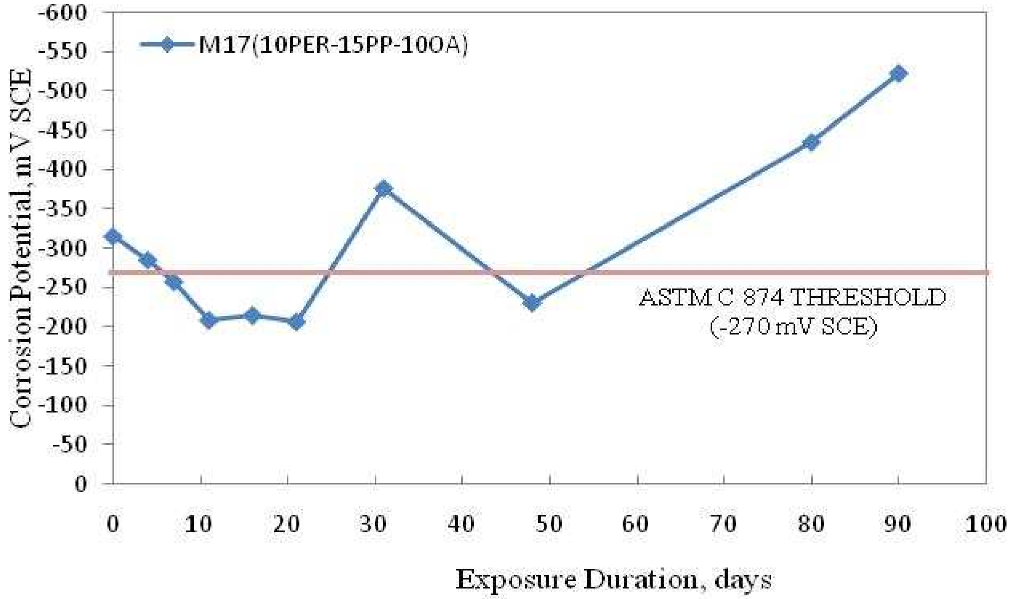
Exposure Duration, days	Corrosion Potential , mV SCE										
	M17	M21	M23	M24	M25	M27	M28	M29	M30	M31	M32
0	-316	-183	-236	-218	-340	-344	-450	-362	-188	-404	-310
4	-286	-151	-268	-166	-213	-273	-307	-229	-143	-198	-283
7	-258	-141	-320	-460	-198	-246	-267	-213	-150	-177	-267
11	-209	-146	-472	-494	-189	-252	-243	-210	-141	-164	-256
16	-216	-142	-483	-378	-307	-293	-220	-220	-137	-157	-249
21	-208	-138	-484	-305	-327	-265	-211	-216	-130	-156	-243
31	-377	-131	-476	-312	-404	-475	-194	-203	-119	-151	-239
48	-232	-136	-295	-235	-323	-223	-197	-205	-126	-162	-246
80	-435	-136	-317	-259	-313	-211	-171	-209	-125	-177	-241
90	-523	-131	-325	-270	-353	-200	-166	-173	-127	-230	-261

The corrosion potentials of the SLWC mixes will be discussed for each specimen and in the same group as done earlier.

4.9.1 Mixes containing Perlite and Polypropylene (M17, M23-M25)

The average corrosion potentials over a period of 90 days, for each mix in this group, are plotted in Figure 4.25.

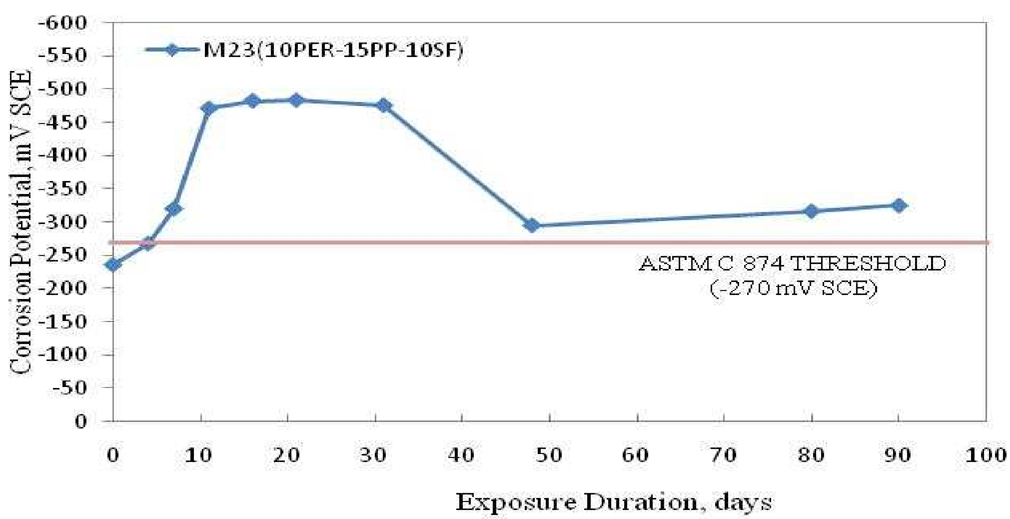
4.9.1.1 Mix M17 (10PER-15PP-10OA)



(a): Corrosion potentials on steel in mix M17.

The average corrosion potentials varied with time and crossed the value of -270 mV SCE after 54 days. The corrosion potential after 90 days was -532 mV SCE.

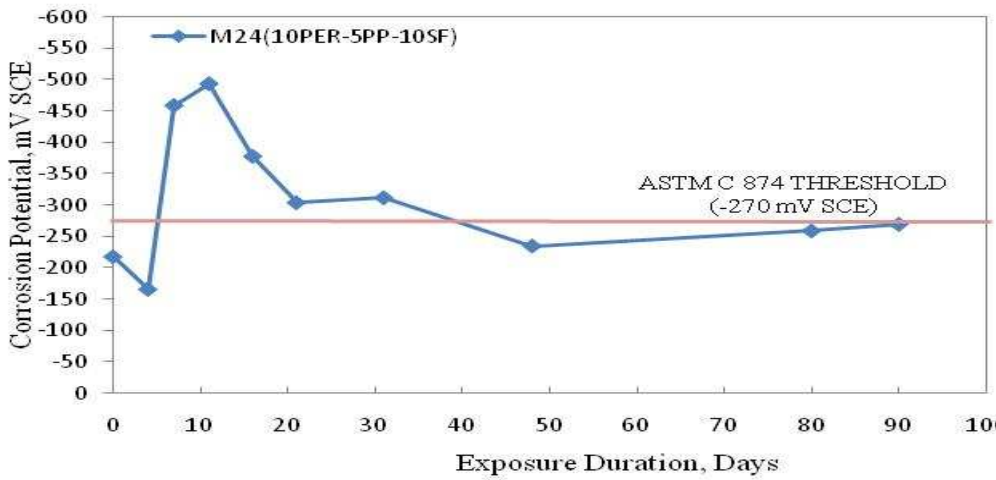
4.9.1.2 Mix M23 (10PER-15PP-10SF)



(b): Corrosion potentials on steel in mix M23.

The average corrosion potentials exceeded the threshold value of -270 mV SCE after 4 days. The corrosion potential after 90 days was -325 mV SCE.

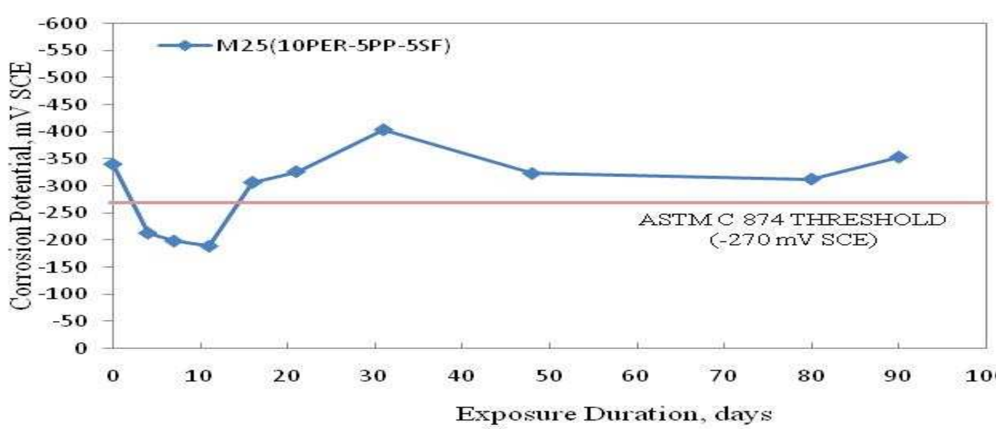
4.9.1.3 Mix M24 (10PER-5PP-10SF)



(c): Corrosion potentials on steel in mix M24.

The average corrosion potentials crossed the threshold of -270 mV SCE after only 4 days. The corrosion potential after 90 days was -270 mV SCE.

4.9.1.4 Mix M25 (10PER-5PP-5SF)



(d): Corrosion potentials on steel in mix M25.

Figure 4.25: Corrosion potentials on steel in mixes with perlite and polypropylene.

The average corrosion potentials exceeded the threshold value of -270 mV SCE after only 14 days. The corrosion potential after 90 days was -353 mV SCE.

In the mixes with perlite and polypropylene, the maximum corrosion potentials value, after 90 days of exposure in %5 NaCl solution, was -532 mV SCE measured in mix (M17) having the highest percentage of polypropylene (15%), perlite (10%), and the highest percentage of oil ash (10%).The lowest corrosion potentials value of -270 mV SCE was recorded in mix (M24) having the lowest percentage of polypropylene (5%),perlite (10%), and the highest percentage of silica fume (10%).All the mixes in this group exceeded the corrosion potentials threshold at different periods.

In mixes M23 and M24, with the same percentage of perlite and silica fume, the reduction in polypropylene percentage from 15% in (M23) to 5% in (M24)decreased the corrosion potential value from -325 to -270 mV SCE in 90 days.

In mixes M17 and M23, with the same percentage of perlite and polypropylene, the oil ash has a higher corrosion potentials value than silica fume as its specimen (M17) has -523 mV compared to -325 mV for the silica fume specimen (M23).

4.9.2 Mixes containing Perlite and Scoria (M21, M27, M29-M32)

The average corrosion potentials values for each mix in this group are plotted in Figure 4.26.

4.9.2.1 Mix M21 (10PER-25SC-10SF)

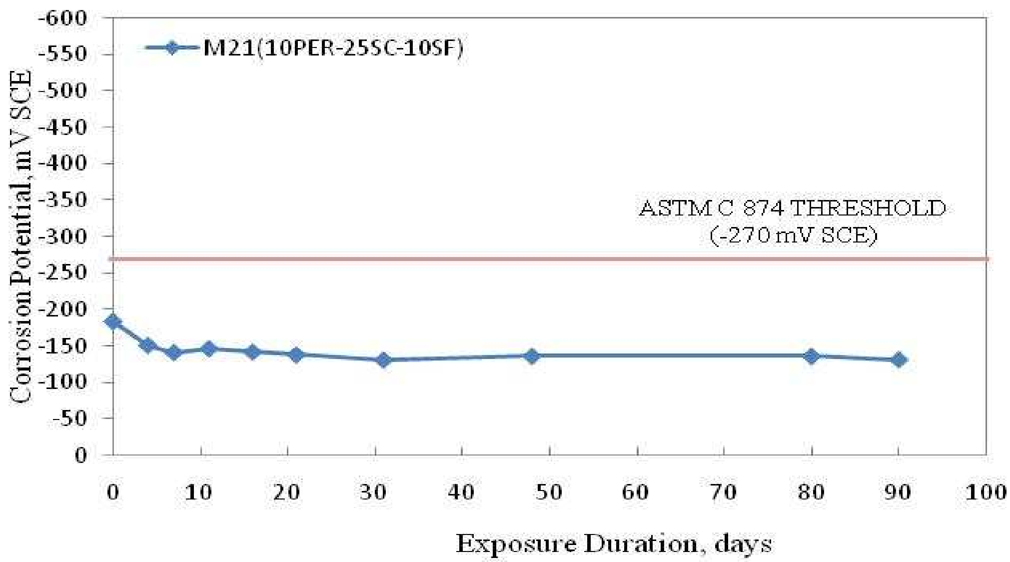
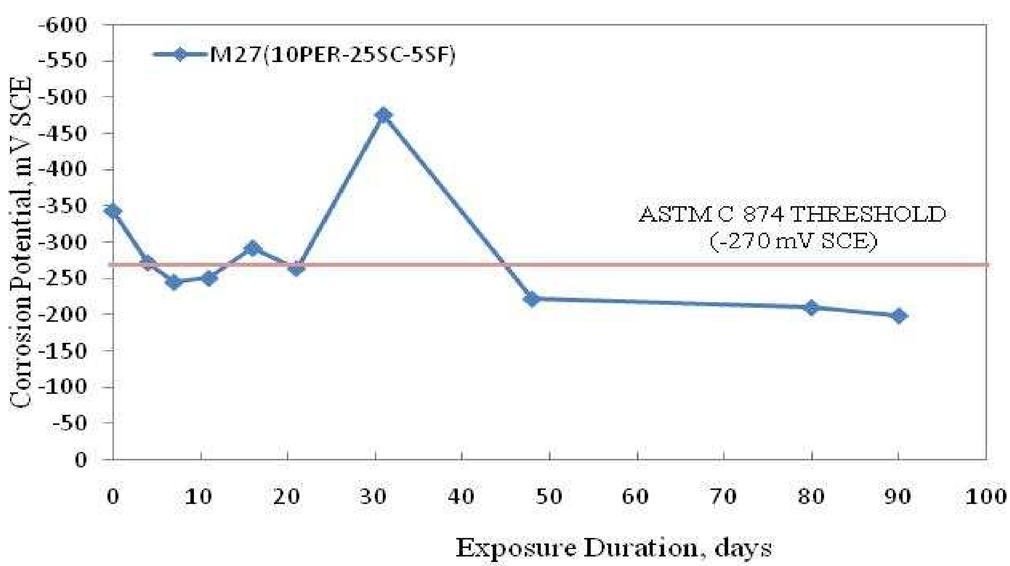


Figure (a): Corrosion potentials on steel in mix M21.

The average corrosion potentials didn't cross the threshold value of -270 mV SCE even after 90 days. The corrosion potential after 90 days was -131 mV SCE.

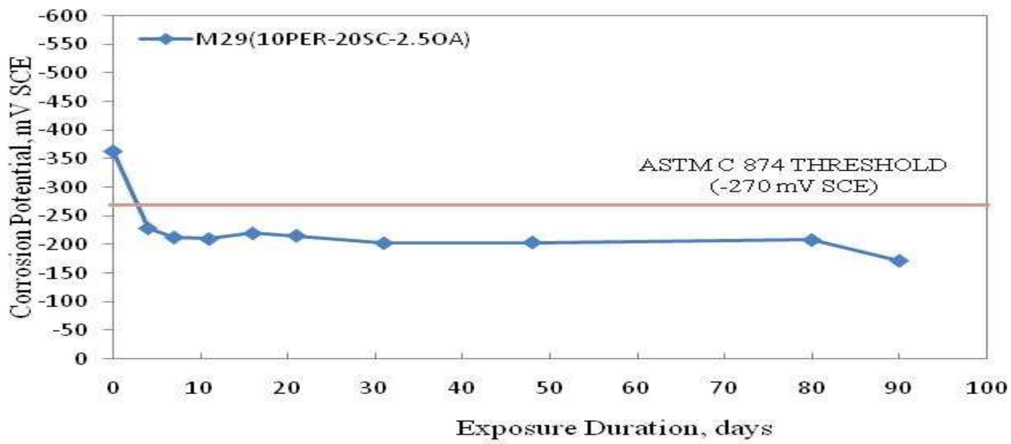
4.9.2.2 Mix M27 (10PER-25SC-5SF)



(b): Corrosion potentials on steel in mix M27.

The average corrosion potentials fluctuated down and up the threshold of -270 mV SCE. The average corrosion potential after 90 days was -200 mV SCE.

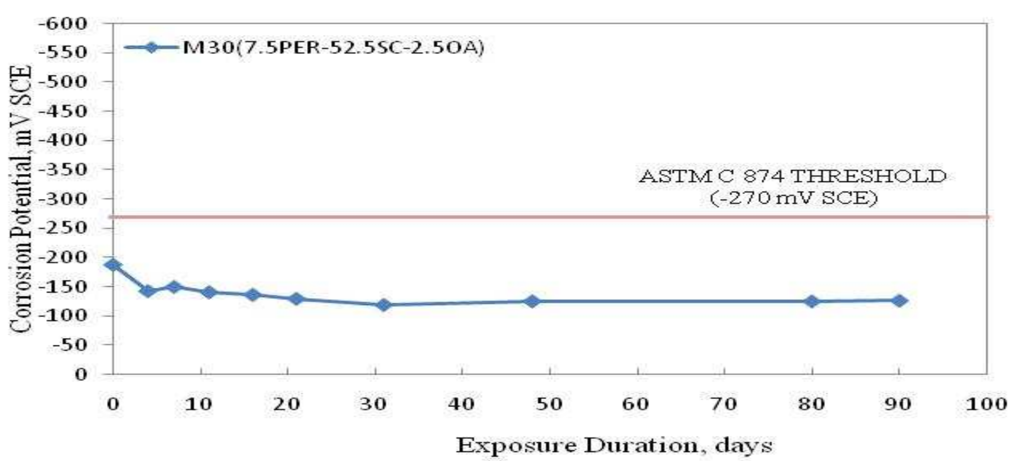
4.9.2.3 Mix M29 (10PER-20SC-2.5OA)



(c): Corrosion potentials on steel in mix M29.

The corrosion potentials were less than the threshold value of -270 mV SCE even after 90 days of exposure. The average corrosion potential after 90 days was -173 mV SCE.

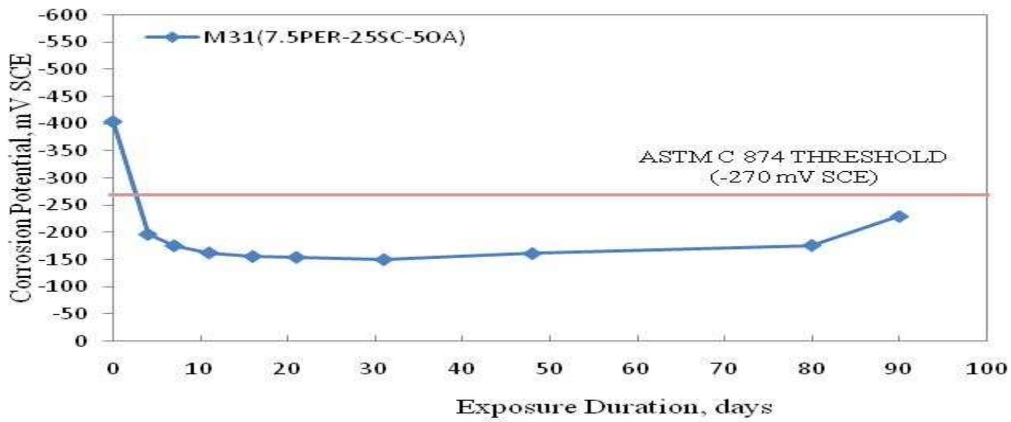
4.9.2.4 Mix M30 (7.5PER-52.5SC-2.5OA)



(d): Corrosion potentials on steel in mix M30.

In this specimen also the average corrosion potential was less than the threshold value of -270 mV SCE. The average corrosion potential after 90 days was -127 mV SCE.

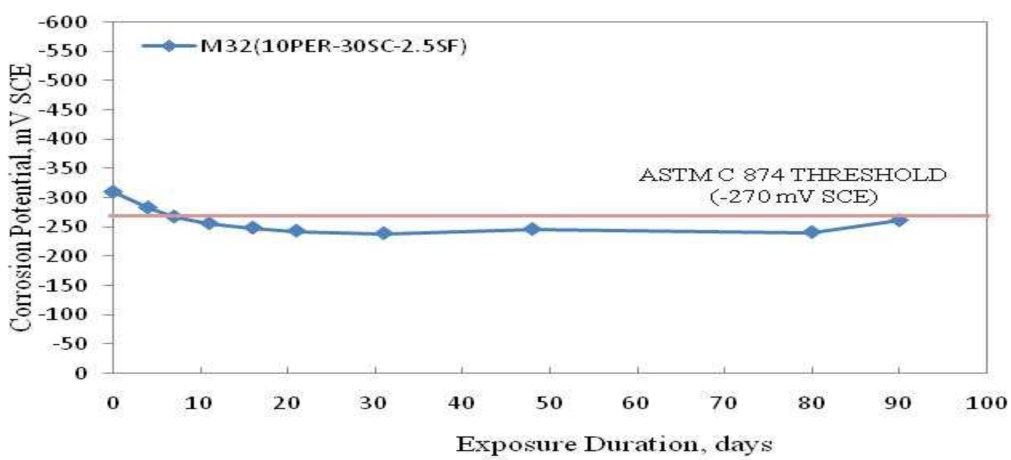
4.9.2.5 Mix M31 (7.5PER-25SC-5OA)



(e): Corrosion potentials on steel in mix M31.

The average corrosion potentials on steel in this mix didn’t exceed the threshold value of -270 mV SCE. The average corrosion potential after 90 days was -230 mV SCE.

4.9.2.6 Mix M32 (10PER-30SC-2.5SF):



(f): Corrosion potentials on steel in mix M32.

Figure 4.26: Corrosion potentials on steel in mixes with perlite and scoria.

In mix M32 the average corrosion potentials did not exceed the threshold value of -270 mV SCE. The average corrosion potential after 90 days was -261 mV SCE.

In the six mixes prepared with perlite and scoria, the highest corrosion potentials value was -261 mV SCE measured in mix (M32) prepared with 30% scoria, 10% perlite, and 2.5% silica fume. The lowest corrosion potentials of -127 mV SCE was recorded in mix (M30) having the lowest percentage of perlite of 7.5%, 52.5% scoria, and 2.5% oil ash.

The corrosion potentials on steel in all mixes in this group did not exceed the corrosion potential threshold value even after 90 days.

4.9.3 Mix containing Perlite without Scoria and polypropylene M28

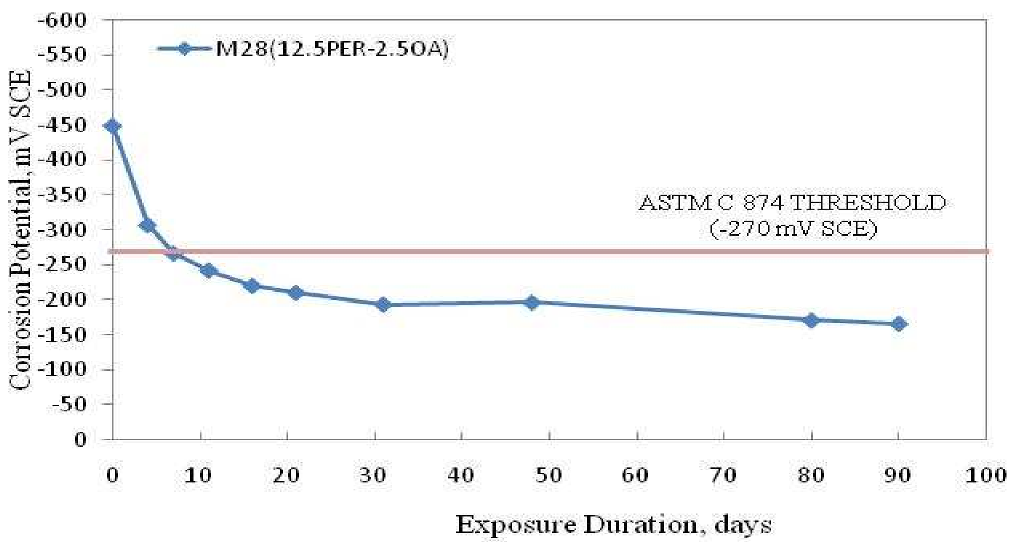


Figure 4.27: Corrosion potentials on steel in mix M28.

The corrosion potentials in this mix were less than -270 mV. The average corrosion potential after 90 days was -166 mV SCE, as shown in Figure 4.27.

4.10 Corrosion current density

The average corrosion current density, Icorr, values of the SLWC cylinder specimens measured over a period of 48 days of exposure to 5% NaCl solution is presented in Table 4.12.

Table 4.12: Corrosion current density on steel in the developed SLWC mixes.

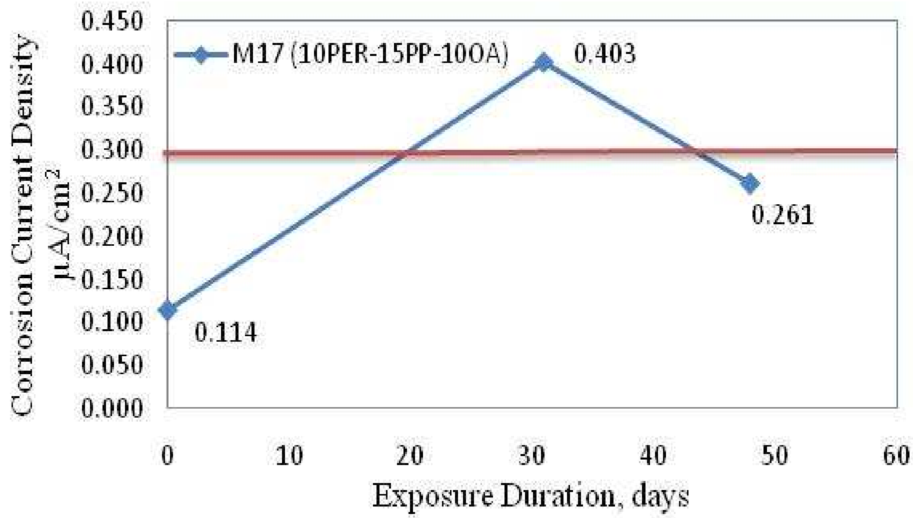
Exposure Duration, days	Corrosion Current Density, Icorr , μA/cm^2										
	M17	M21	M23	M24	M25	M27	M28	M29	M30	M31	M32
0	0.114	0.043	0.063	0.047	0.050	0.025	0.071	0.042	0.030	0.063	0.044
31	0.403	0.016	0.167	0.052	0.036	0.155	0.038	0.003	0.016	0.027	0.022
48	0.261	0.008	0.055	0.036	0.028	0.046	0.031	0.015	0.013	0.031	0.021

The variation of corrosion current density of the developed SLWC mixes will be discussed in three groups as was done earlier.

4.10.1 Mixes containing Perlite and Polypropylene (M17, M23-M25)

The average corrosion current density for this group of specimens is plotted in Figure 4.28.

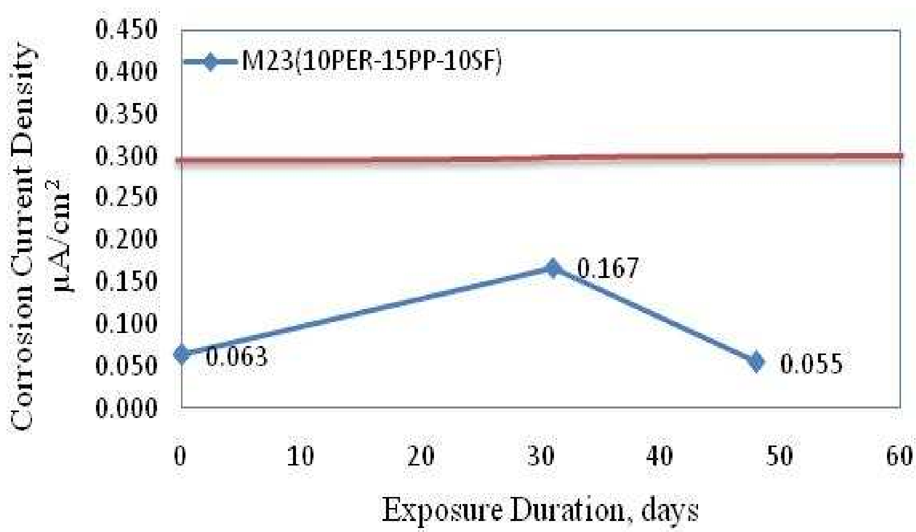
4.10.1.1 M17 (10PER-15PP-10OA)



(a): Mix M17.

The average corrosion current density increased initially, but it decreased thereafter. The Icorr after 48 days of exposure was 0.26 µA/cm^2, less than the threshold value of 0.3µA/cm^2 for corrosion initiation [32].

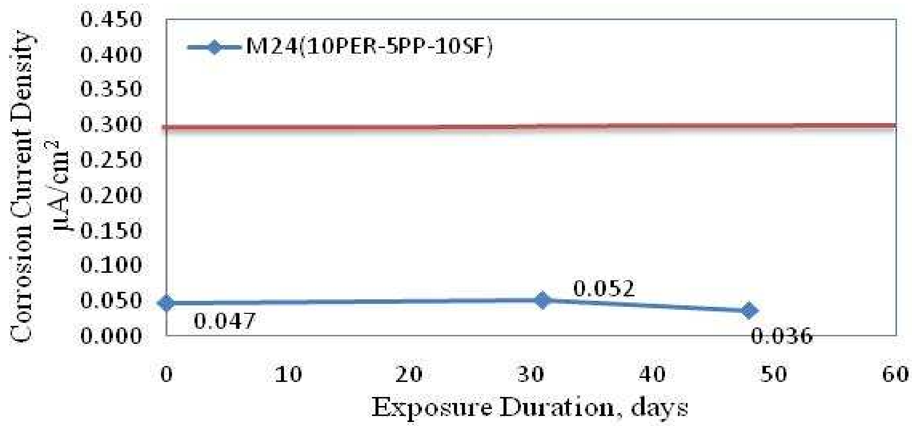
4.10.1.2 Mix M23 (10PER-15PP-10SF)



(b): Mix M23.

The average corrosion current densities in this specimen were less than the threshold value of 0.3 µA/cm^2.The corrosion current density after 48 days was 0.055 µA/cm^2.

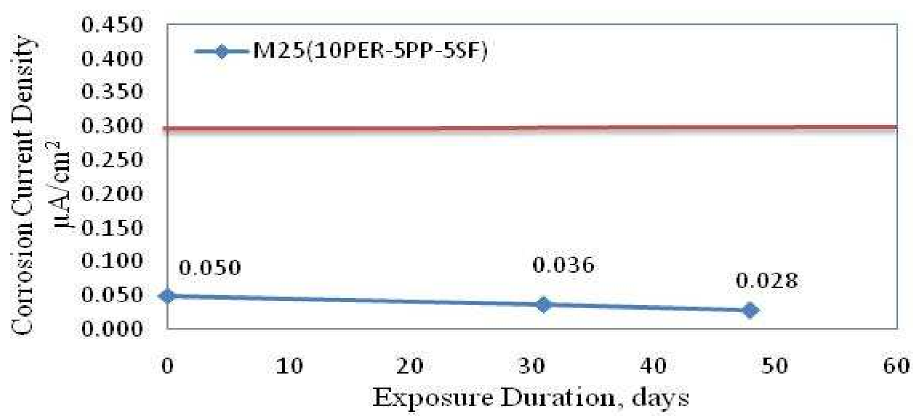
4.10.1.3 Mix M24 (10PER-5PP-10SF)



(c): Mix M24.

The average corrosion current densities were less than the threshold value of 0.3 µA/cm^2. The corrosion current density after 48 days was 0.036 µA/cm^2.

4.10.1.4 Mix M25 (10PER-5PP-5SF)



(d): Mix M25.

Figure 4.28: Corrosion current density on steel in SLWC specimens prepared with perlite and polypropylene.

The average corrosion current densities in this specimen didn’t exceed the threshold value of 0.3 μA/cm^2. The corrosion current density after 48 days was 0.028 μA/cm^2.

In the mixes with perlite and polypropylene, The highest corrosion current density value, after 48 days of exposure in %5 NaCl solution, was 0.26 μA/cm^2 measured in mix (M17) prepared with the highest percentage of polypropylene (15%), perlite (10%), and the highest percentage of oil ash (10%).The lowest corrosion current density value of 0.028 μA/cm^2 was recorded in mix (M25) having the lowest percentage of polypropylene (5%),perlite (10%), and silica fume (5%).The corrosion current density in all the mixes in this group did not exceed the threshold value of 0.3μA/cm.

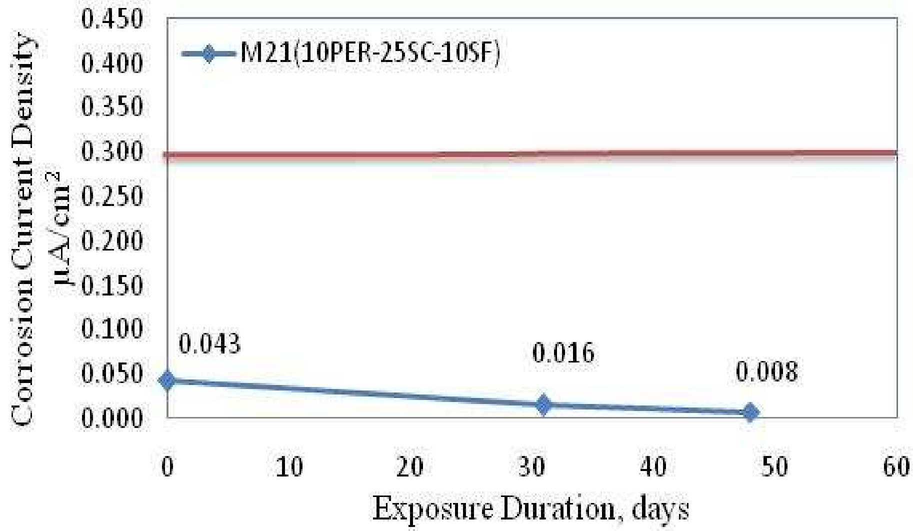
In mixes M23 and M24, with the same percentage of perlite and silica fume, a reduction in the quantity of polypropylene from 15% in (M23) to 5% in (M24) decreased the corrosion current density value from 0.055 to 0.036 μA/cm^2.

In mixes M17 and M23, with the same percentage of perlite and polypropylene, the corrosion current density on specimen with oil ash was more than that in silica fume specimen.

4.10.2 Mixes containing Perlite and Scoria (M21, M27, M29-M32)

The corrosion current density on steel in SLWC mixes in this group is plotted in Figure 4.29.

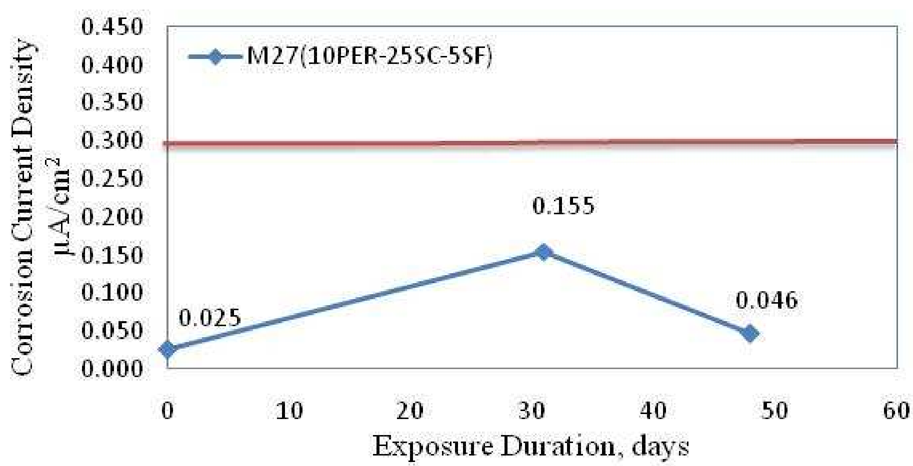
4.10.2.1 Mix M21 (10PER-25SC-10SF)



(a): Mix M21.

The average corrosion current densities in this specimen did not exceed the threshold value of 0.3 µA/cm^2. The corrosion current density after 48 days was 0.008 µA/cm^2.

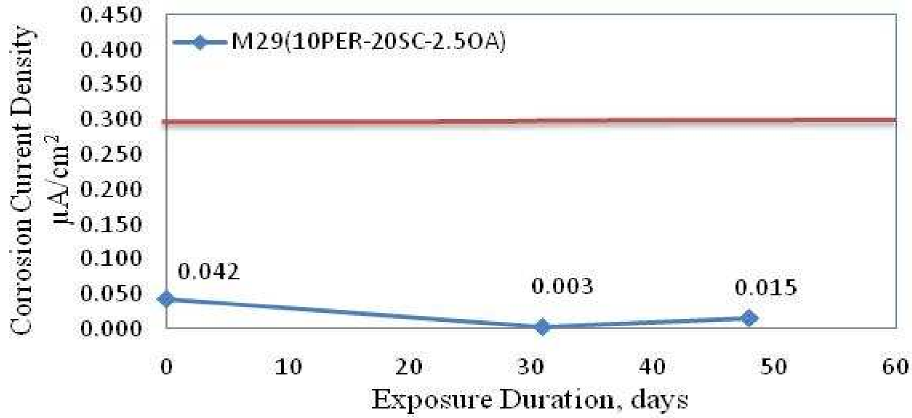
4.10.2.2 Mix M27 (10PER-25SC-5SF)



(b): Mix M27.

The average corrosion current densities didn't exceed the threshold value of 0.3 µA/cm^2. The corrosion current density in this specimen after 48 days was 0.046 µA/cm^2.

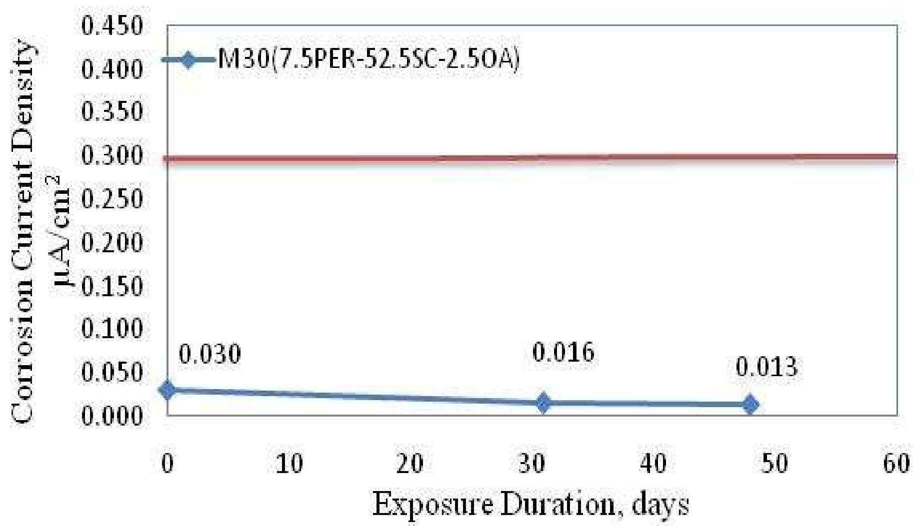
4.10.2.3 Mix M29 (10PER-20SC-2.5OA)



(c): Mix M29.

The average corrosion current densities in this specimen were less than 0.3 µA/cm^2. In this specimen the corrosion current density after 48 days was 0.015 µA/cm^2.

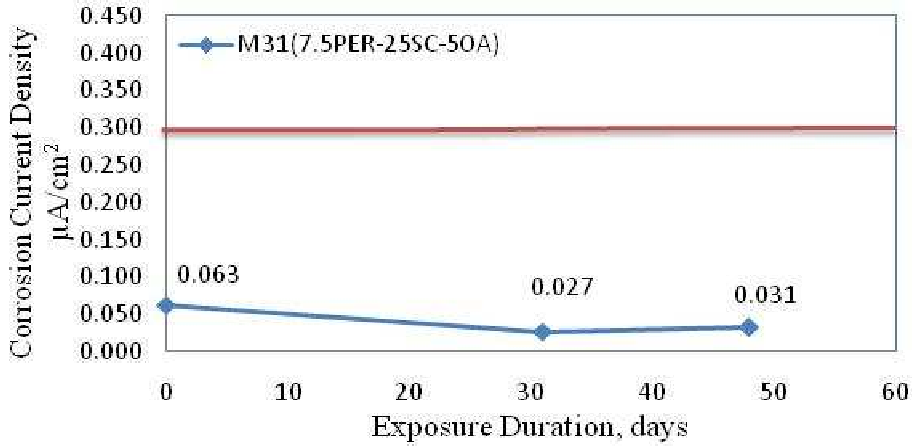
4.10.2.4 Mix M30 (7.5PER-52.5SC-2.5OA)



(d): Mix M30.

The average corrosion current densities did not exceed the threshold value of 0.3 µA/cm^2. The corrosion current density after 48 days was 0.013 µA/cm^2.

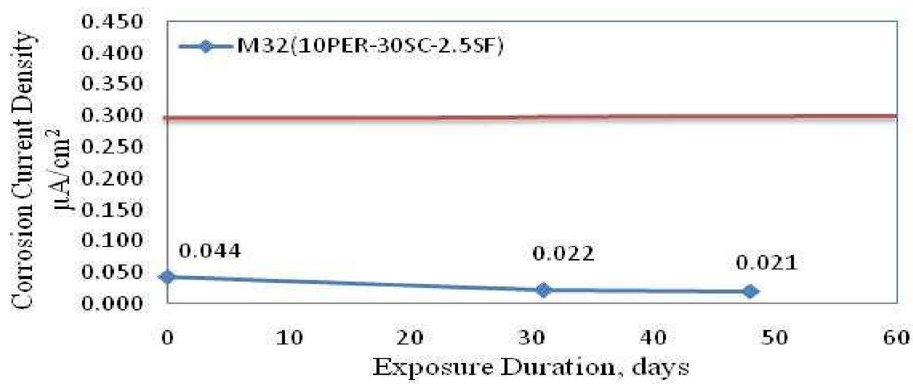
4.10.2.5 Mix M31 (7.5PER-25SC-5OA)



(e): Mix M31.

The average corrosion current densities were less than the threshold value of 0.3 µA/cm^2. The corrosion current density in this mix after 48 days was 0.031 µA/cm^2.

4.10.2.6 Mix M32 (10PER-30SC-2.5SF)



(f): Mix M32.

Figure 4.29: Corrosion current density on steel in SLWC specimens prepared with perlite and scoria

The average corrosion current densities in this specimen were less than the threshold value of 0.3 µA/cm^2. The corrosion current density after 48 days was 0.021 µA/cm^2.

In the six mixes of perlite and scoria combination group, the highest corrosion current density value was 0.046 µA/cm^{2}measured in Mix (M27) with a scoria of 25%, 10% perlite, and silica fume of 5%.The lowest corrosion current density was 0.008 µA/cm^2 recorded in Mix (M21) having a scoria of 25%, 10% perlite, and 10 % silica fume. The corrosion current density in all the mixes of this group of specimens was less than 0.3 µA/cm^2.

4.10.3 Mix containing Perlite without Scoria and polypropylene M28

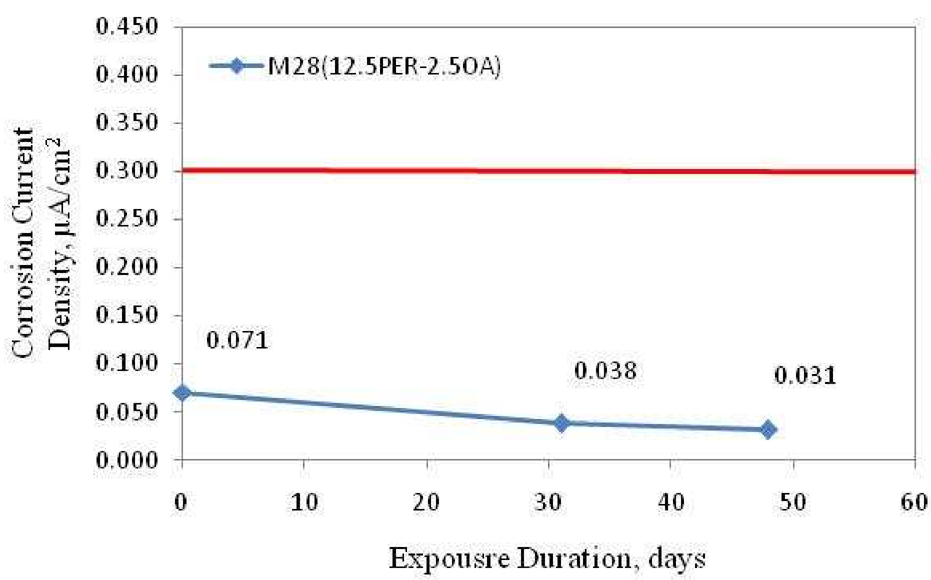


Figure 4.30: Corrosion current density on steel in mix M28.

The average corrosion current densities in this mix were less than the threshold value of 0.3 µA/cm^2.The corrosion current density after 48 days was 0.031 µA/cm^2, see Figure 4.30.

CHAPTER 5

CONCLUSIONS, RECOMMENDATIONS AND FUTURE WORK

5.1 Conclusions

The aim of this study was to produce structural lightweight concrete with the use of local natural light weight aggregates, such as expanded perlite aggregate and scoria aggregate, artificial aggregates, like polypropylene, and industrial waste byproduct like oil ash, with low thermal conductivity. The following conclusions can be drawn based on the data developed in this study.

5.1.1 Mixes containing Perlite, Polypropylene, and Oil ash or Silica fume

1. The 28-day unit weight of the SLWC specimens in this group varied from 1674 kg/m^3 1785 kg/m^{3}satisfying the requirement of structural lightweight concrete.
2. The compressive strength of the produced SLWC in this group was between 21.3 MPa to 25.8 MPa satisfying the requirement of structural lightweight concrete.
3. The modulus of rupture MOR of the developed SLWC in this group was between 1.95-3.47 MPa being within the limit of normal concrete.
4. The water absorption of the SLWC samples in this group was between 8.9-12.6%.

5. The chloride permeability of the developed SLWC in this group was very low, except in mix M17.The high percentage of oil ash used in this mix increased the chloride permeability.

6. The thermal conductivity of the SLWC samples in this group was between 0.413-0.657 W/m.K which is low compared to the thermal conductivity of normal concrete that is between 1.185-1.448 W/m.K. This makes the developed SLWC suitable for modern buildings that require thermal insulation properties.

7. The drying shrinkage of SLWC specimens in this group, after 92 days exposure in laboratory condition, was between 1784 to 1090 microns, and all samples exceeded the 7days threshold value in 2-4 days, except mix M17 that exceeded the threshold value after 18 days due to the high percentage of oil ash used that reduced the drying shrinkage.

8. The corrosion potentials of the developed SLWC in this group after 90 days of exposure in 5% NaCl solution was between -270 mV to -532 mV SCE, and the threshold value of -270 mV SCE was exceeded in 4-54 days of exposure .

9. The corrosion current density on steel in the SLWC specimens in this group after 48 days of exposure to 5% NaCl solution was between 0.028-0.26 $\mu A/cm^2$ that is less than the threshold value of 0.3 $\mu A/cm^2$.

5.1.2 Mixes containing Perlite, Scoria, and Oil ash or Silica fume

1. The 28-day unit weight of the SLWC samples in this group varied from 1830 kg/m^3 to 1891 kg/m^3satisfying the requirement of structural lightweight concrete.
2. The compressive strength of the produced SLWC in this group was between 35.4 MPa and 21 MPa satisfying the requirement of structural lightweight concrete.
3. The modulus of rupture MOR of the developed SLWC in this group was between 3.41 and 3.92 MPa.
4. The water absorption of the SLWC specimens in this group was between 6.5 and 9.4 %.
5. The chloride permeability of the developed SLWC specimens in this group was between 738 and 2875 coulombs being very low to moderate.
6. The thermal conductivity of the SLWC specimens in this group was between 0.362 and 0.483 W/m.K which is low compared to the thermal conductivity of normal concrete that is between 1.185-1.448 W/m.K.
7. The drying shrinkage of SLWC specimens in this group, after 92 days exposure in laboratory condition, was between 638 and 1235 microns, and all specimens exceeded the 7days threshold value after 7days.
8. The corrosion potentials on steel in the developed SLWC specimens in this group after 90 days of exposure in 5% NaCl solution was between -127 mV and -261mVSCE, these values were less than and the threshold of -270 mV SCE in this period.

9. The corrosion current density of the SLWC specimens in this group after 48 days of exposure in 5% NaCl solution is between 0.008 and 0.046 $\mu A/cm^2$, that is less than the threshold value of 0.3 $\mu A/cm^2$.

5.1.3 Mix containing Perlite (without Scoria and Polypropylene) and Oil Ash

1. The 28-day unit weight of this mix was1771 kg/m^3satisfying the requirement of structural lightweight concrete.
2. The compressive strength of his SlWC specimen was 19.7 MPa satisfying the requirement of structural lightweight concrete but it is low because of the high percentage of perlite used.
3. The modulus of rupture MOR of this SLWC was 3.08 MPa.
4. The 28-day water absorption of this SLWC was 8.3%.
5. The chloride permeability of this SLWC was 1863 coulombs (low chloride permeability).
6. The thermal conductivity of this SLWC was 0.393 W/m.K which is low compared to the thermal conductivity of normal concrete that is between 1.185-1.448 W/m.K, this makes this SLWC suitable for modern buildings that require thermal insulation properties.
7. The drying shrinkage of this SLWC, after 92 days exposure in laboratory condition, was 1175 microns. The drying shrinkage was more than the 7days threshold value after 7days.

8. The corrosion potential of this SLWC after 90 days of exposure in 5% NaCl solution was -166 mV SCE, and the potentials were below the thresholdvalueof-270 mV SCE in this period.
9. The corrosion current density on steel in this specimen after 48 days of exposure to 5% NaCl solution was0.031 $\mu A/cm^2$ that is less than the threshold value of 0.3 $\mu A/cm^2$.

5.2 Recommendations and Applications

1. Concrete mixtures prepared with perlite, polypropylene, and oil ash or silica fume have shown very low unit weight, moderate compressive strength, high modulus of rupture, and low corrosion resistance. Consequently, these mixes can be used as SLWC in non-corrosive environments.
2. Concrete mixtures prepared with perlite, scoria, and oil ash or silica fume have exhibited low unit weight, high compressive strength, high modulus of rupture, and high corrosion resistance. Consequently, these mixes can be used as SLWC in corrosive and non-corrosive environment.
3. Concrete mixture prepared with perlite, and oil ash has exhibited low unit weight, low compressive strength, high modulus of rupture, and high corrosion resistance. Consequently, this mix can be used as SLWC in corrosive and non-corrosive environment.
4. The use of the expanded perlite aggregate should be limited to 10% of total aggregate in order to get SLWC, as the increase in the quantity of perlite

significantly reduced the compressive strength. Also, the use of more than 5% polypropylene of total aggregate is not recommended for the same reasons.

5. The quantity of oil ash should not exceed 5% of the total aggregate as it causes problems in workability.

5.3 Future Research

i. Develop SLWC using other local lightweight aggregates and other indigenous waste materials.

ii. Investigate other durability characteristics like fire and noise resistance of the developed SLWC.

iii. Develop long-term data for better prediction of durability of SLWC with local materials.

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